The Sterile Neutrino and New Technology for Short-Baseline Reactor Experiments

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Fermilab Neutrino Seminar

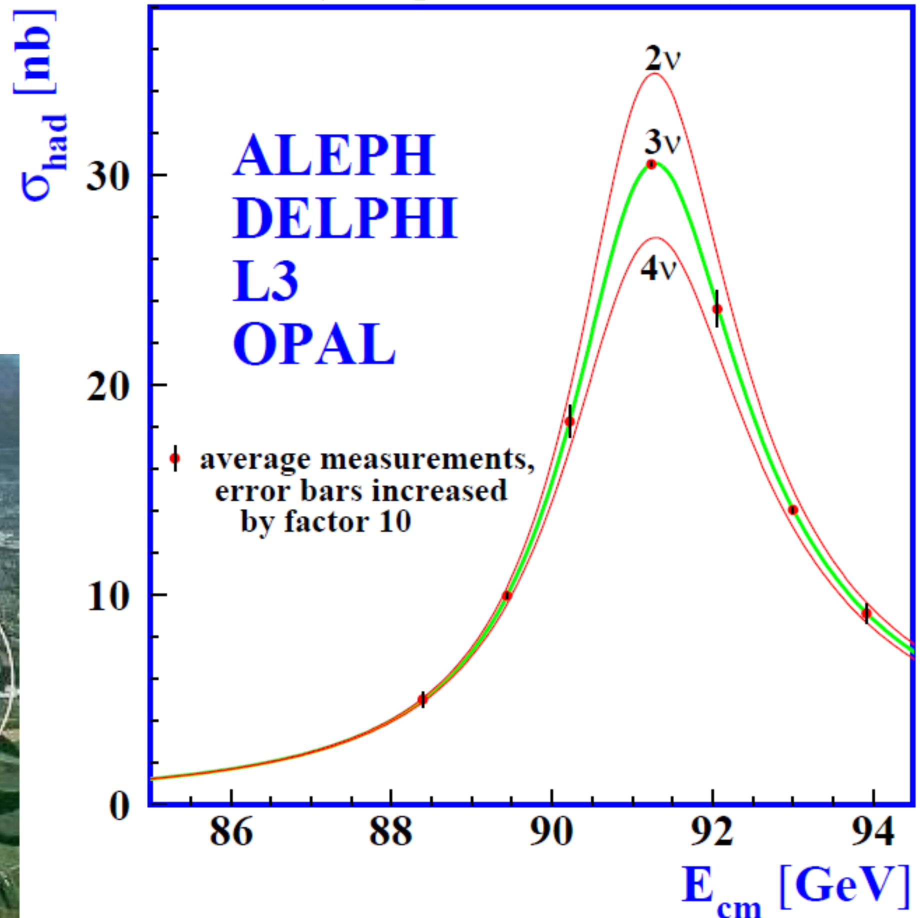
January 28, 2016

Sterile Neutrinos

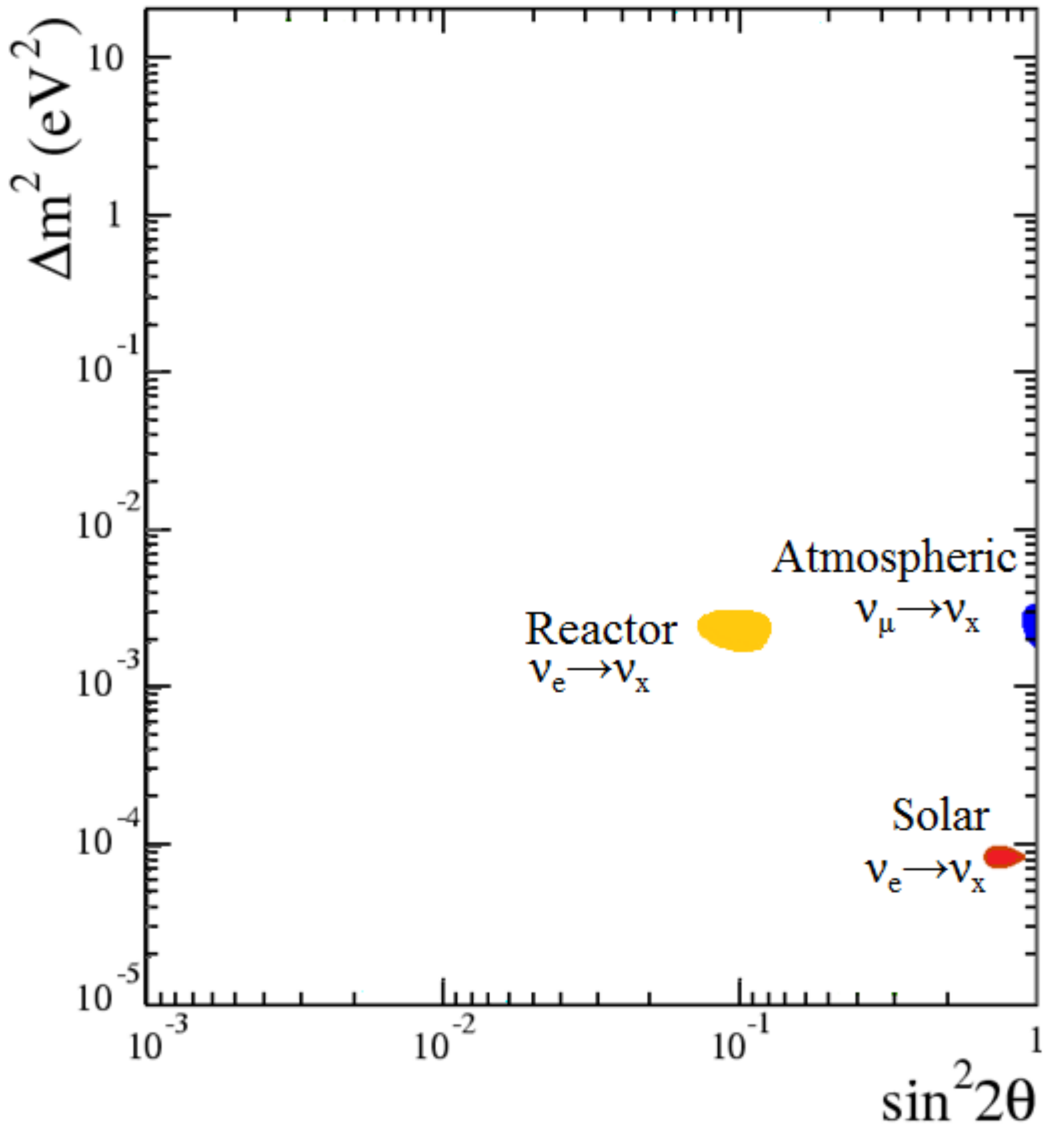
A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Active neutrinos:
LEP Invisible Z^0 Width is consistent with only three light active neutrinos

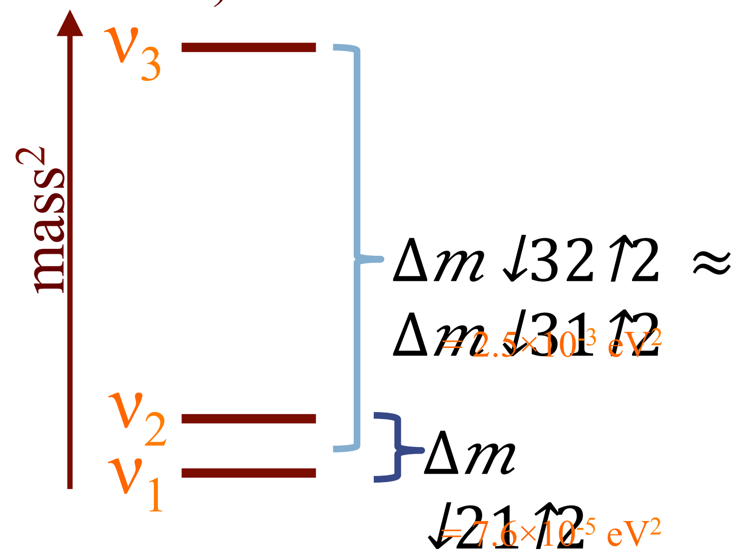
Phys.Rept. 427, 257 (2006)



The Neutrino Oscillation Data



The data for the three neutrino mixing model is nearly complete and extraordinarily self-consistent: (θ_{12}, θ_{23}, θ_{13}, Δm_{21}^2, Δm_{31}^2, and Δm_{32}^2 are measured, δ_{CP} unknown)

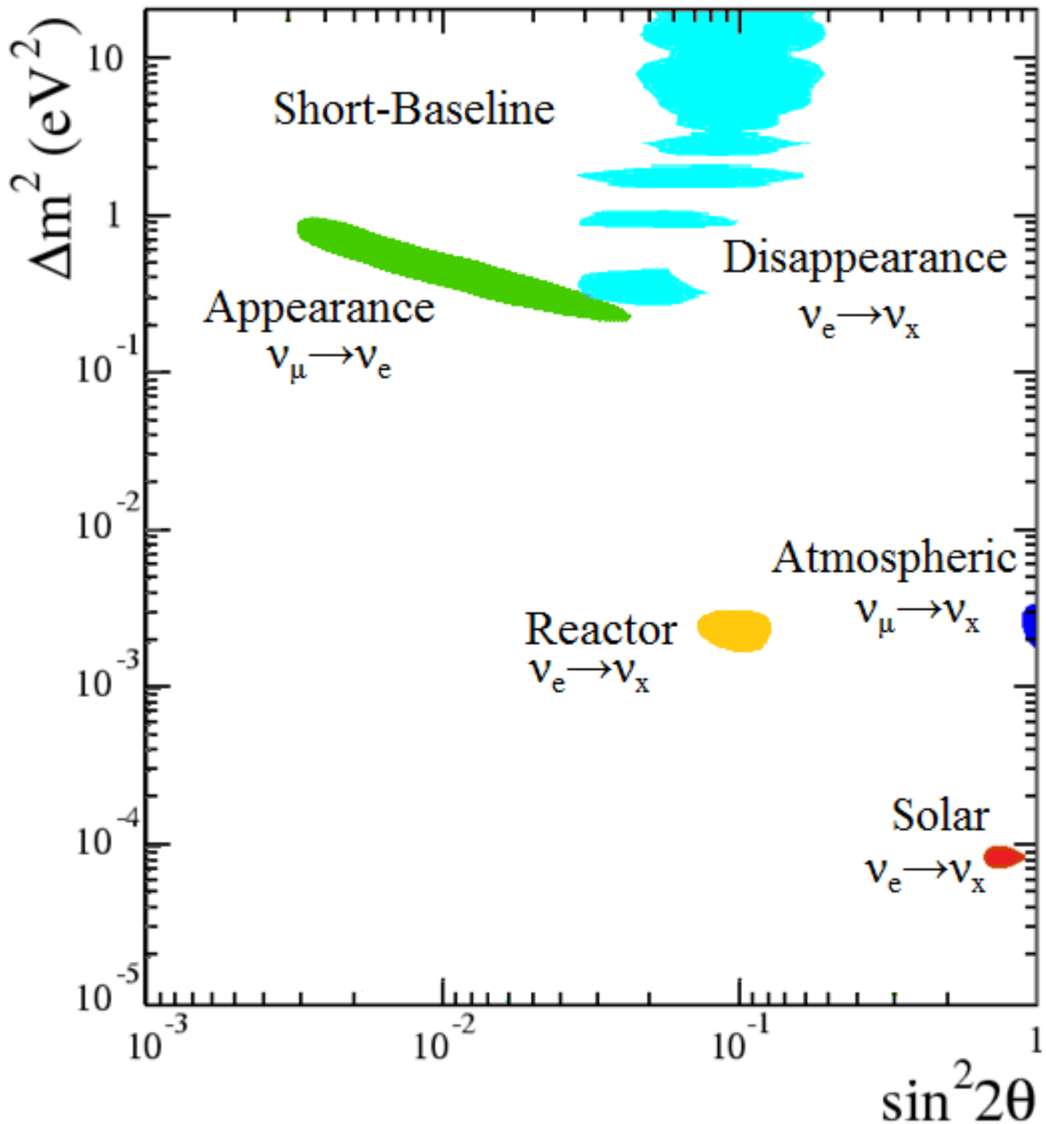


The Laurels Have Already Been Handed Out…

2015 Nobel Prize in Physics:
Takaaki Kajita of Super-K and
Arthur B. McDonald of SNO

2016 Breakthrough Prize in Fundamental Physics:
To the members of the Super-K, SNO KamLAND,
Daya Bay, K2K and T2K Collaborations.

The Neutrino Oscillation Data



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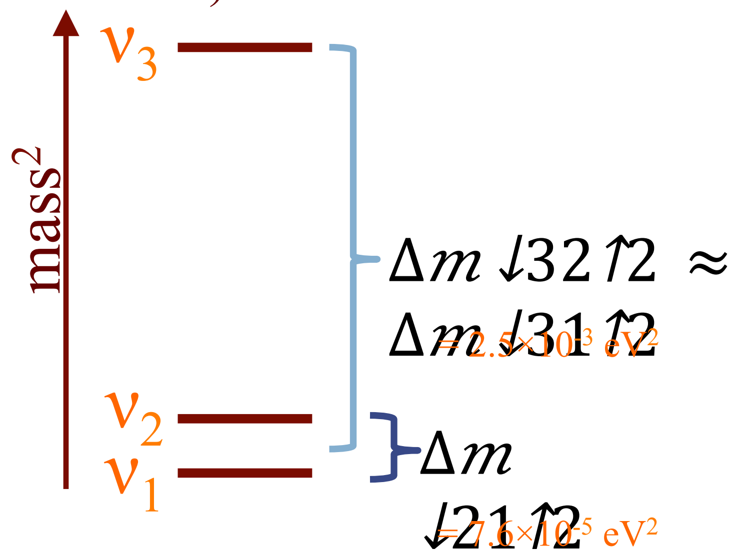
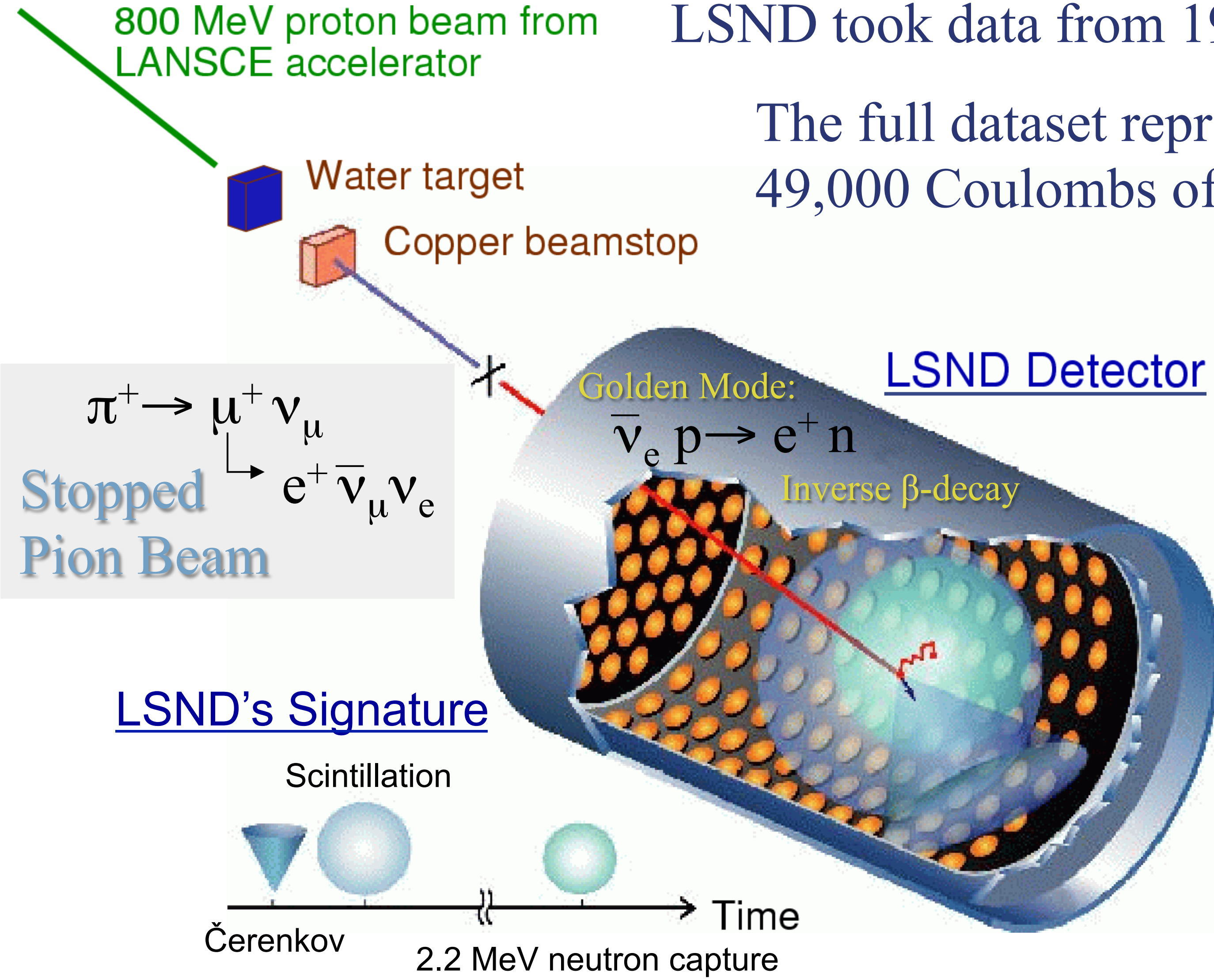


$\Delta m^{2} \sim 1$eV^2 does not fit the three neutrino model

The LSND Experiment

LSND took data from 1993-98

The full dataset represents nearly 49,000 Coulombs of protons on target.



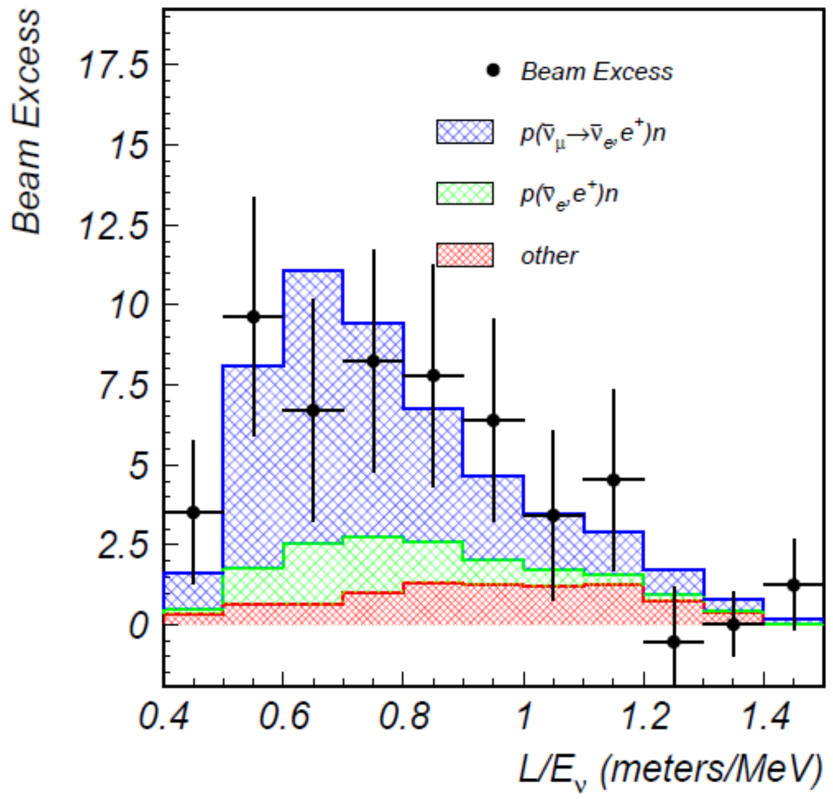
Baseline: 30 m

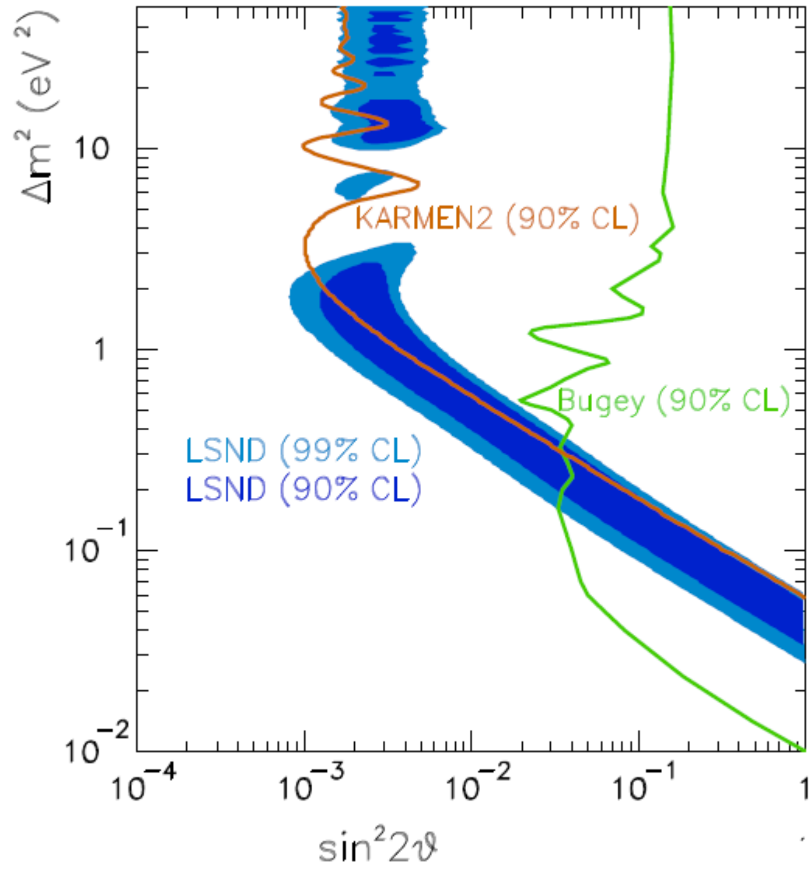
Energy range: 20 to 55 MeV

L/E ~ 1 m/MeV

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

Aguilar-Arevalo *et al.*, Phys.Rev. D64, 112007 (2001)

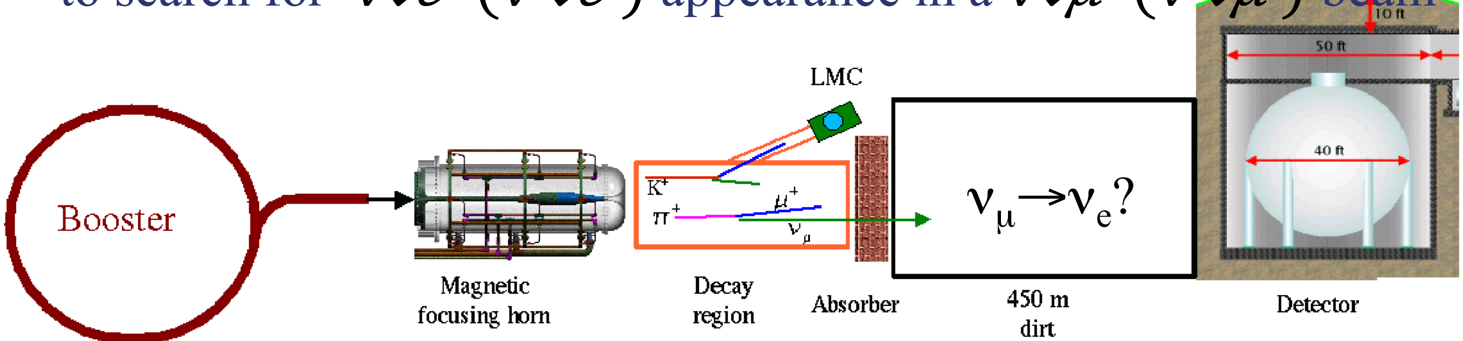




Event Excess: 32.2 ± 9.4 ± 2.3

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

MiniBooNE used a π^+ (π^-) decay in flight beam and a liquid Cherenkov detector to search for ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam

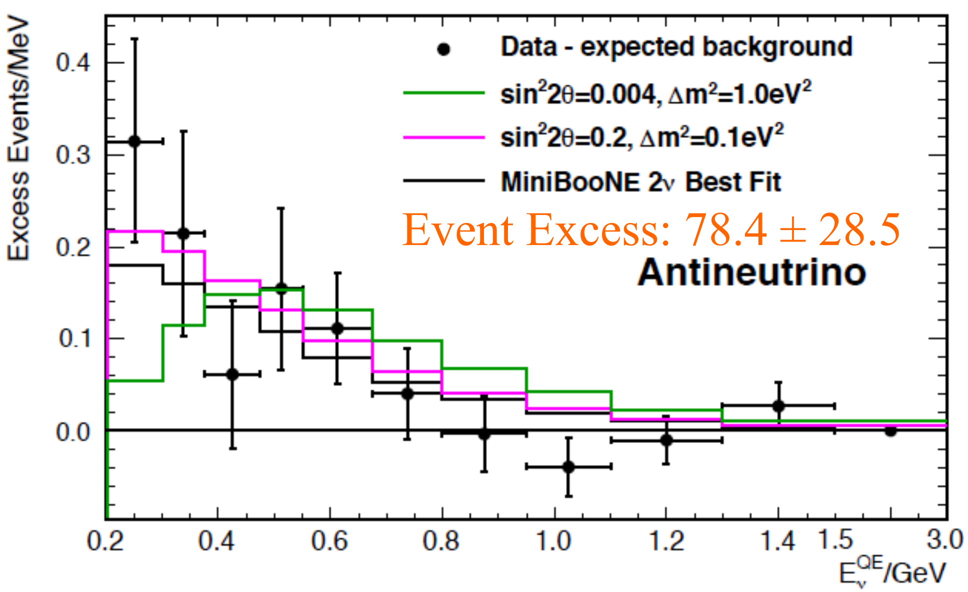


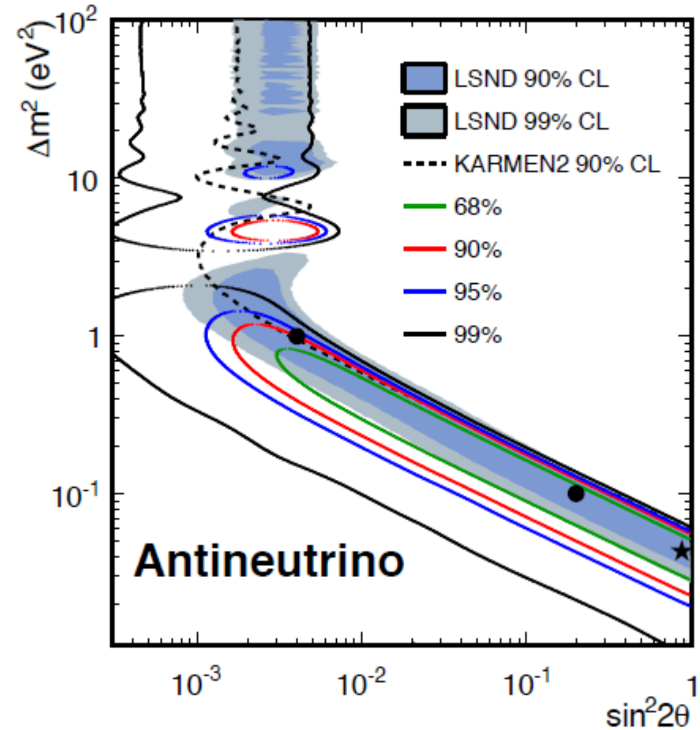
Baseline ~ 500 m

$\langle E_\nu \rangle$ ~ 500 Me

L/E ~ 1 m/MeV

Phys.Rev.Lett. 110, 161801 (2013)





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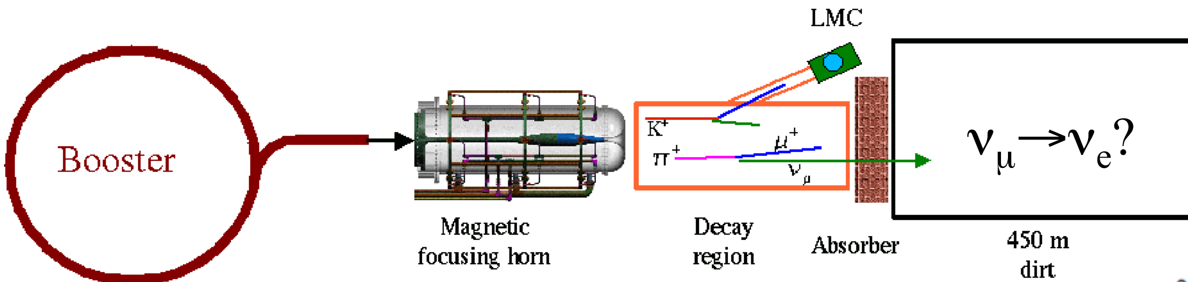

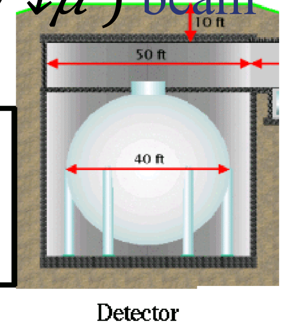

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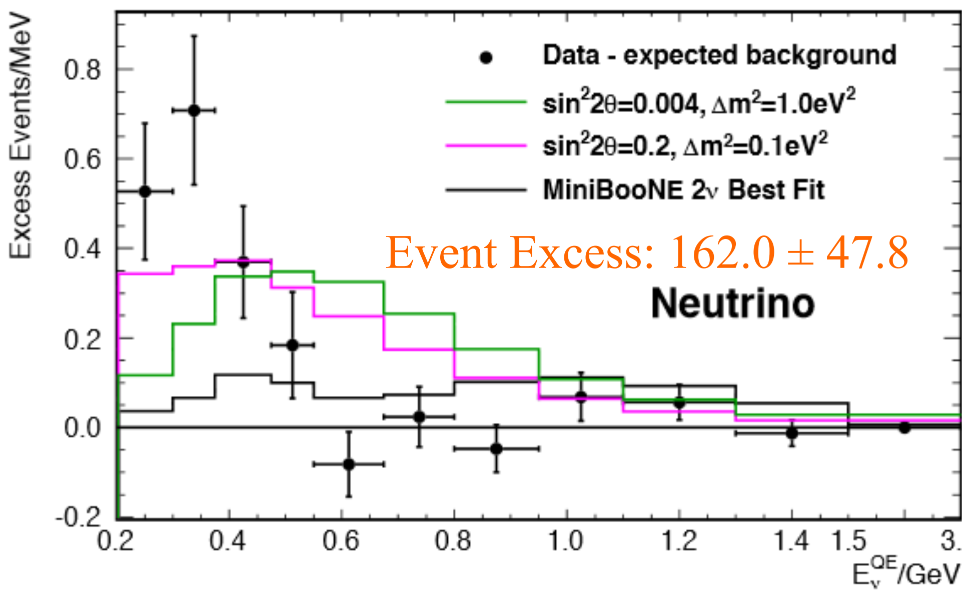
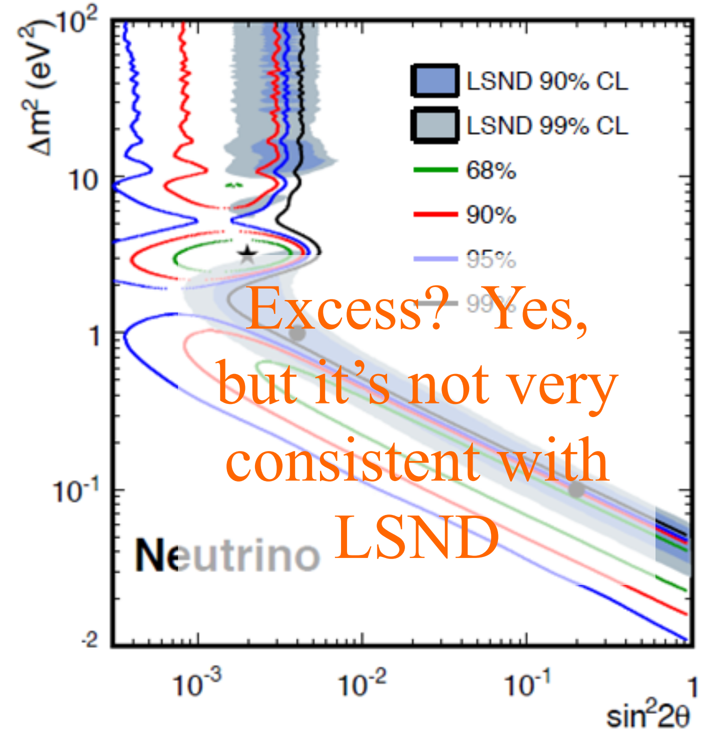


Event Excess: 162.0 ± 47.8

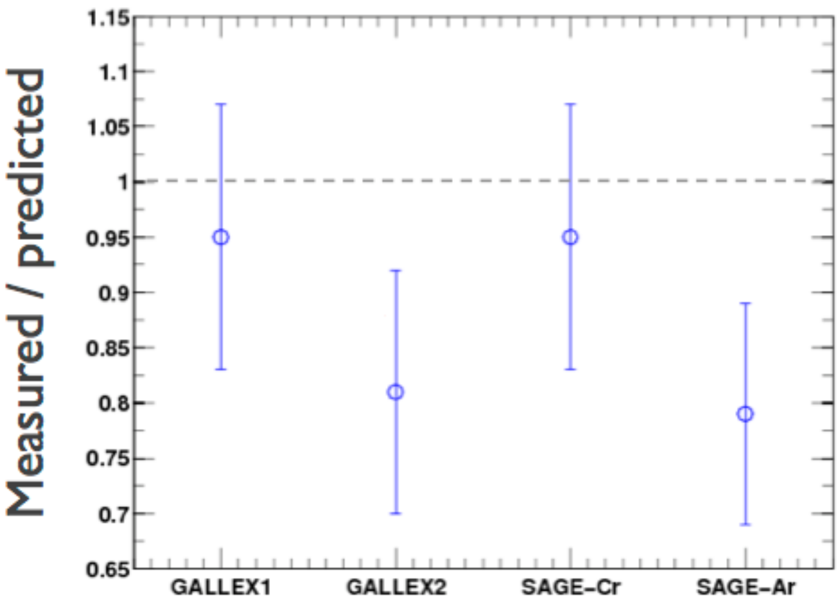


Excess? Yes, but it's not very consistent with LSND

Gallium Anomaly (ν_e Disappearance)

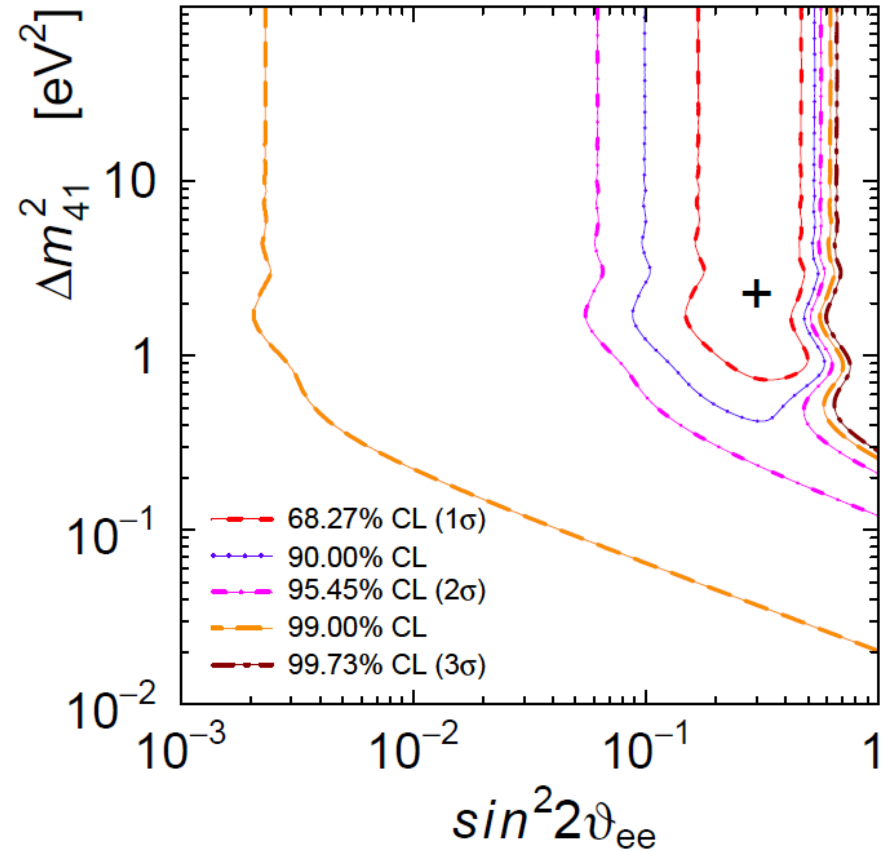
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to "calibrate" the $\nu_e\,^{71}Ga$ interaction/detection rate.

A reanalysis, based on new cross section calculations, suggests that were too few events.

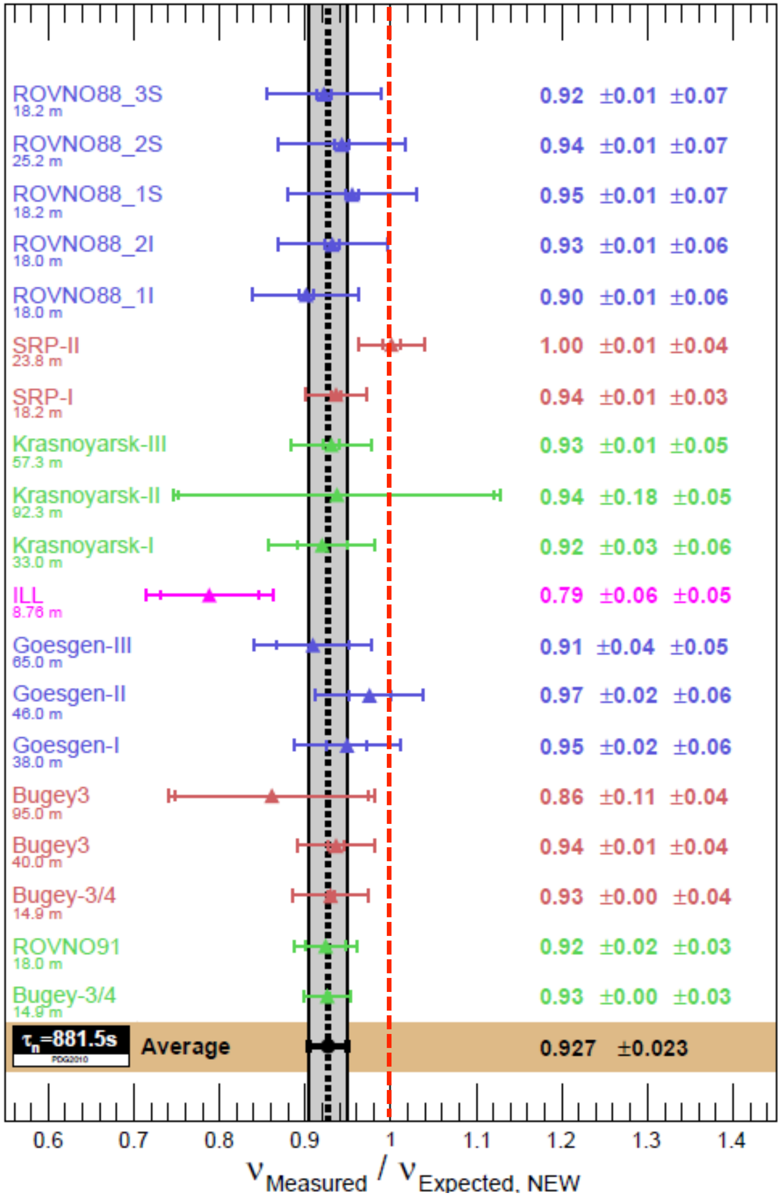


Giunti & Laveder, Phys.Rev.C83, 065504 (2011)

Giunti *et al.*, Phys.Rev.D86, 113014 (2012)

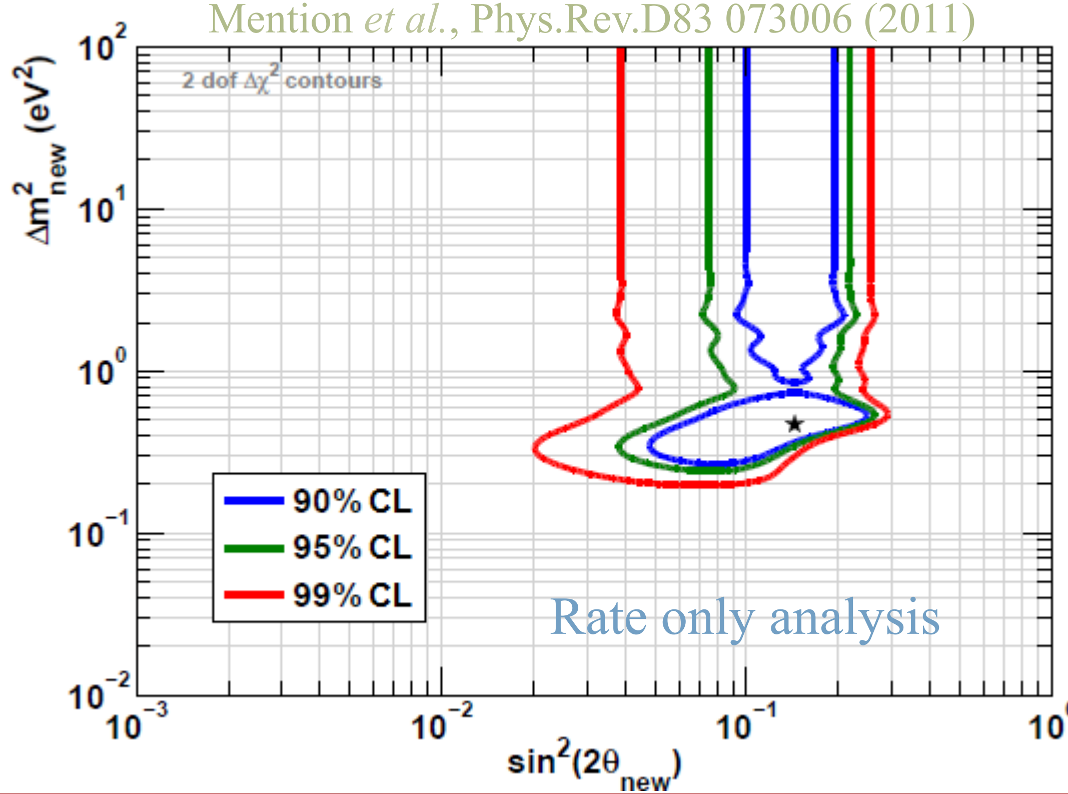


Reactor Anomaly ($\bar{\nu}_e$ Disappearance)



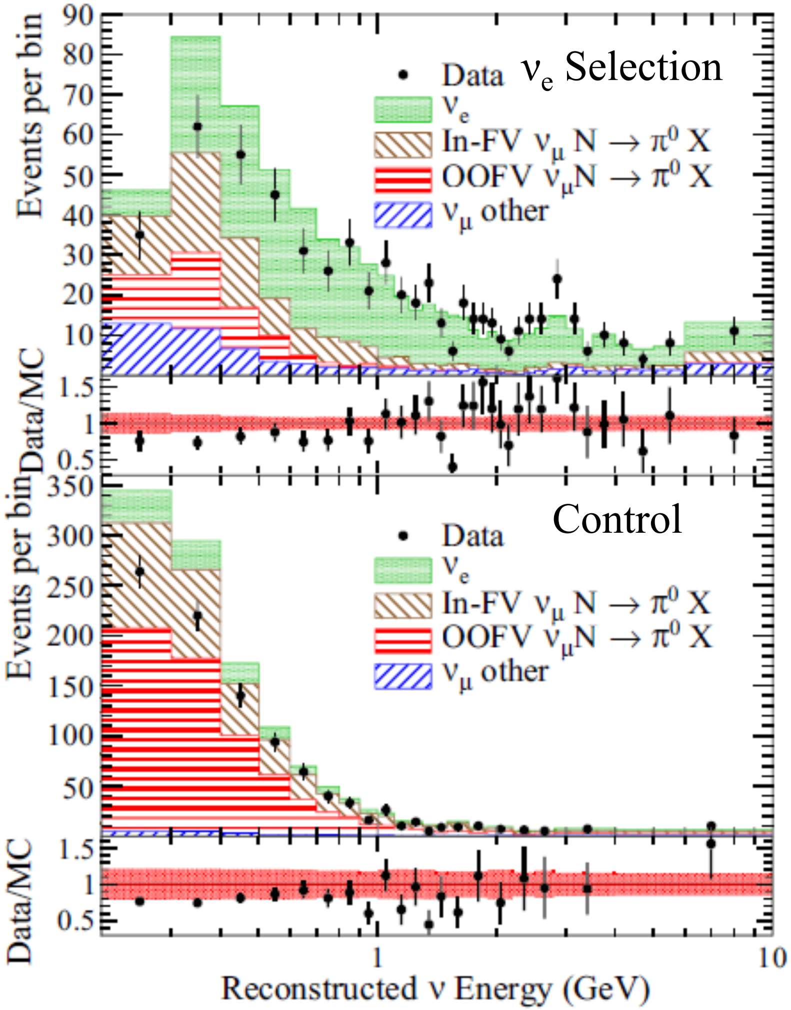
Recent calculations of the reactor ν ↓e flux and spectrum predict a higher rate than the earlier calculation. This resulted is an apparent deficit of reactor neutrinos across all experiments.

Mention *et al.*, Phys.Rev.D83 073006 (2011)

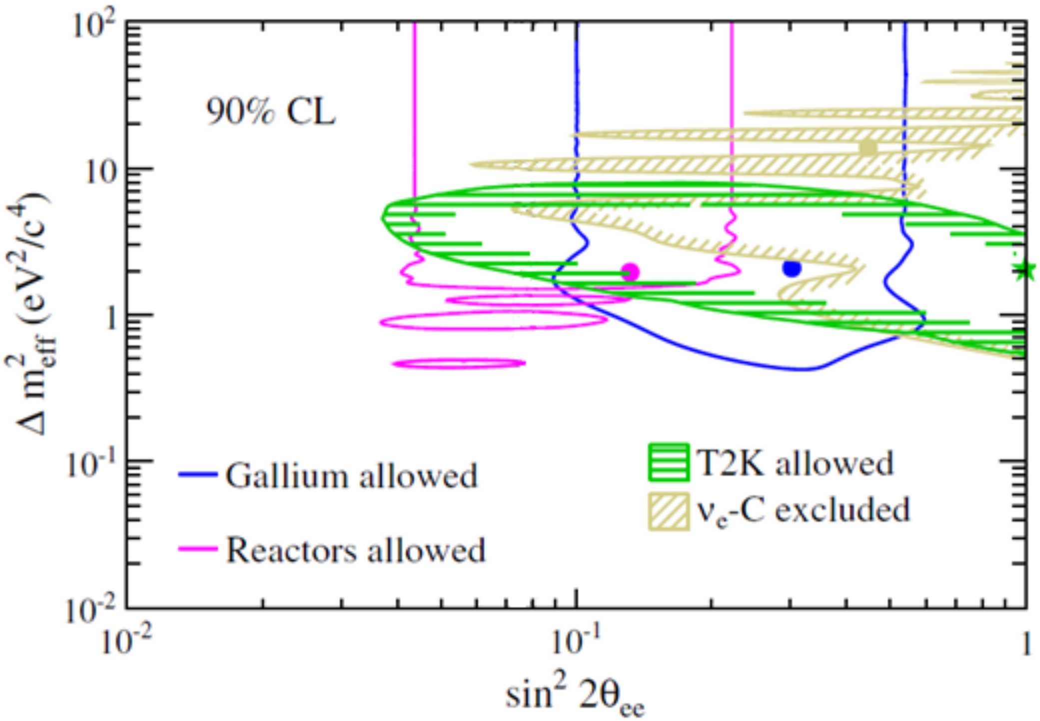


T2K Near Detector (ν_e Disappearance)

Although the T2K beam is predominantly a ν_μ beam, the small ν_e component can be used in the near detector for a ν_e disappearance search.



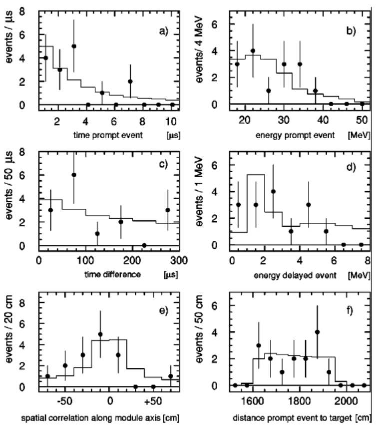
Phys.Rev. D91, 051102(R) (2015)

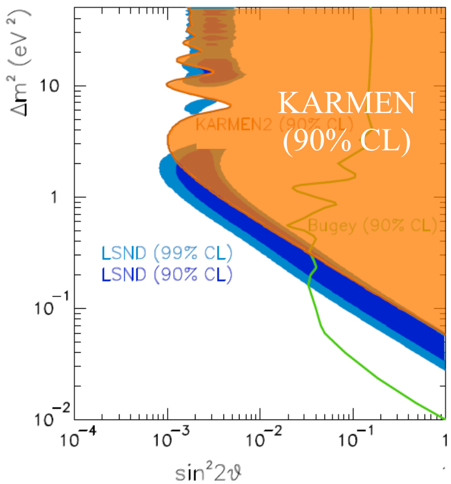


Short-baseline ν_e appearance from the much larger ν_μ component of the beam could fill in the exact region depleted by ν_e disappearance, so $\nu_\mu \rightarrow \nu_e$ is assumed to be zero in this analysis.

Evidence Against the ~1 eV^2 Sterile Neutrino

KARMEN (ν ↓μ →ν ↓e)

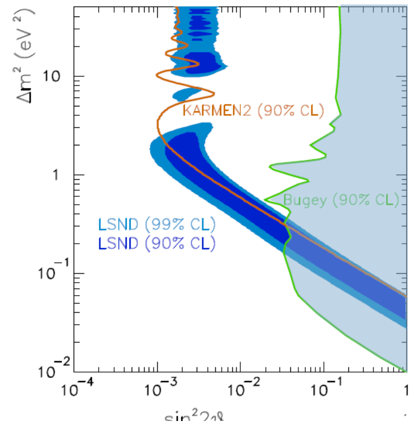


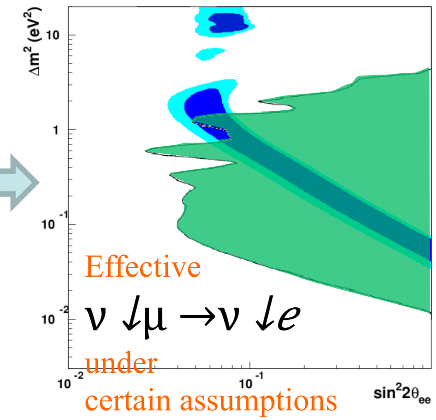


No ν ↓e Excess

Armbruster *et al.*, Phys.Rev.D65 112001 (2002)

Bugey Reactor (ν ↓e Disappearance)

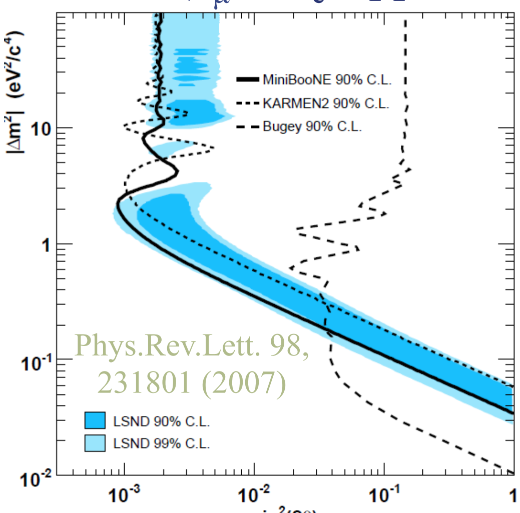




Effective ν ↓μ →ν ↓e under certain assumptions

Achkar *et al.*, Nucl.Phys.B434, 503 (1995)

MiniBooNE ($\nu_\mu \rightarrow \nu_e$ Appearance)



Phys.Rev.Lett. 98, 231801 (2007)

ν_μ Disappearance

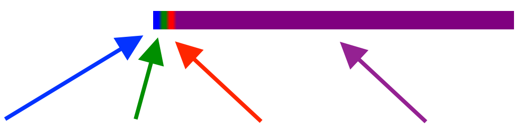
(where is it?)

For ν↓μ →ν↓e to happen there must be both ν↓e and ν↓μ disappearance

Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent Δm^2s.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



$$U_{e4}^2 + U_{\mu4}^2 + U_{\tau4}^2 + U_{s4}^2 = 1 \quad \text{(PMNS Unitarty)}$$

The appearance probability:

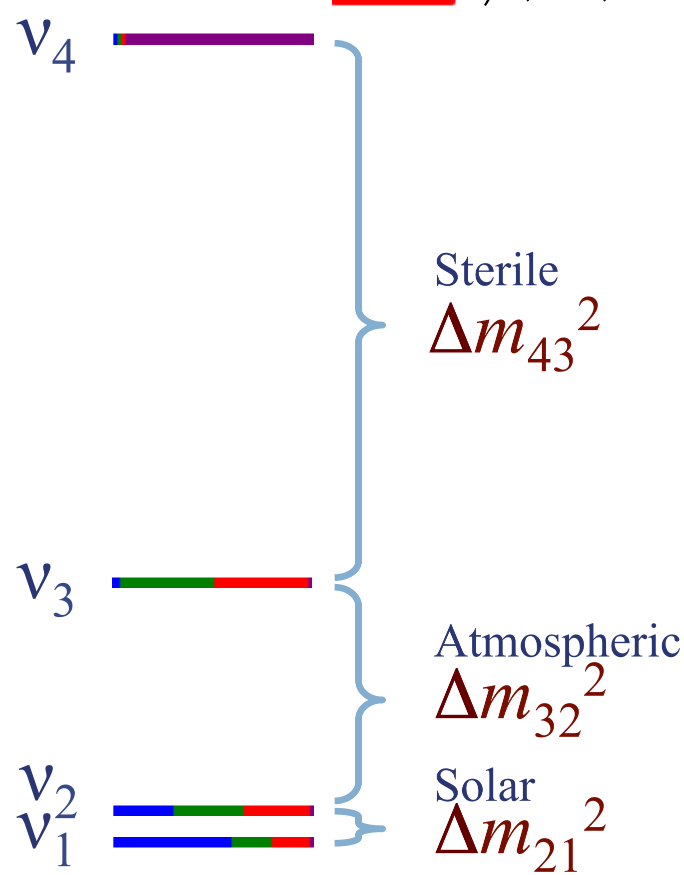
$$P_{\mu e} = 4U_{e4}^2\,U_{\mu4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_e disappearance probability:

$$P_{ee} \approx P_{es} = 4U_{e4}^2\,U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$

The ν_μ disappearance probability:

$$P_{\mu\mu} \approx 4U_{\mu4}^2\,U_{s4}^2 \sin^2(1.27\Delta m_{43}^2 L/E)$$



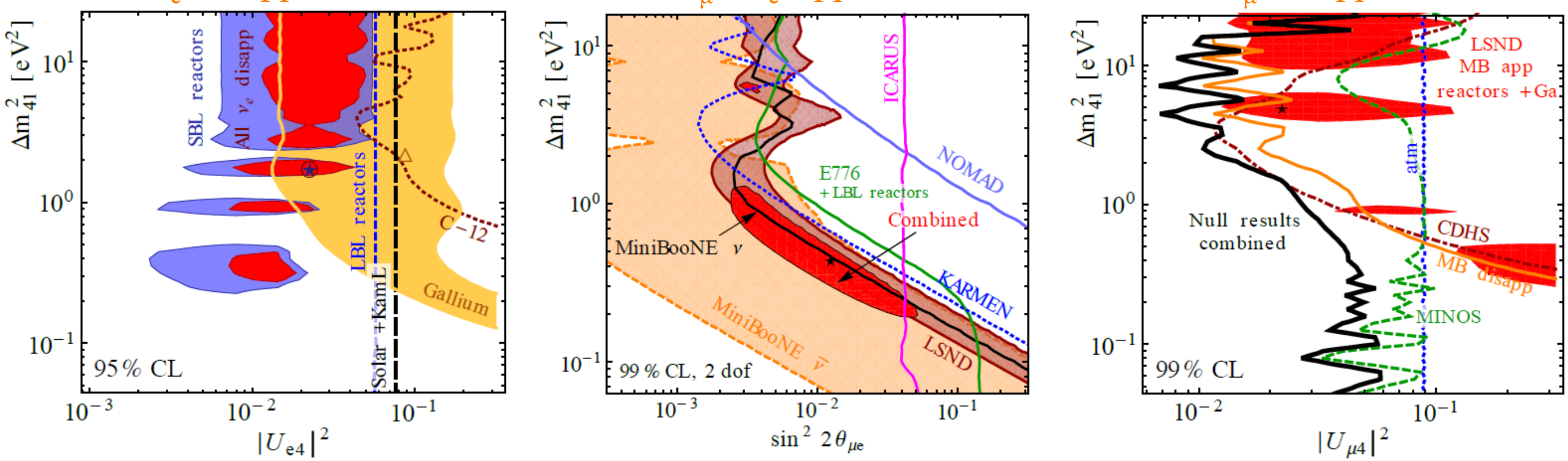
Appearance vs. Disappearance

1. Since any 4[th] mass state is predominantly sterile ($U_{s4} \approx 1$), so…

$P_{\mu e} \approx 1/4 \ P_{ee} \times P_{\mu\mu}$

2. Since $P_{\mu e}$ depends on both U_{e4} and $U_{\mu 4}$, you can have ν_e disappearance without ν_e appearance, but you can't have ν_e appearance without ν_μ disappearance.

ν_e Disappearance | $\nu_\mu \rightarrow \nu_e$ Appearance | ν_μ Disappearance



Global fit from Kopp *et al.* JHEP 1305, 050 (2013)

The absence of ν_μ disappearance is a huge problem for the LSND and MiniBooNE signals, while the ν_e disappearance anomalies are consistent with all existing data.

Requirement for Disappearance Experiments

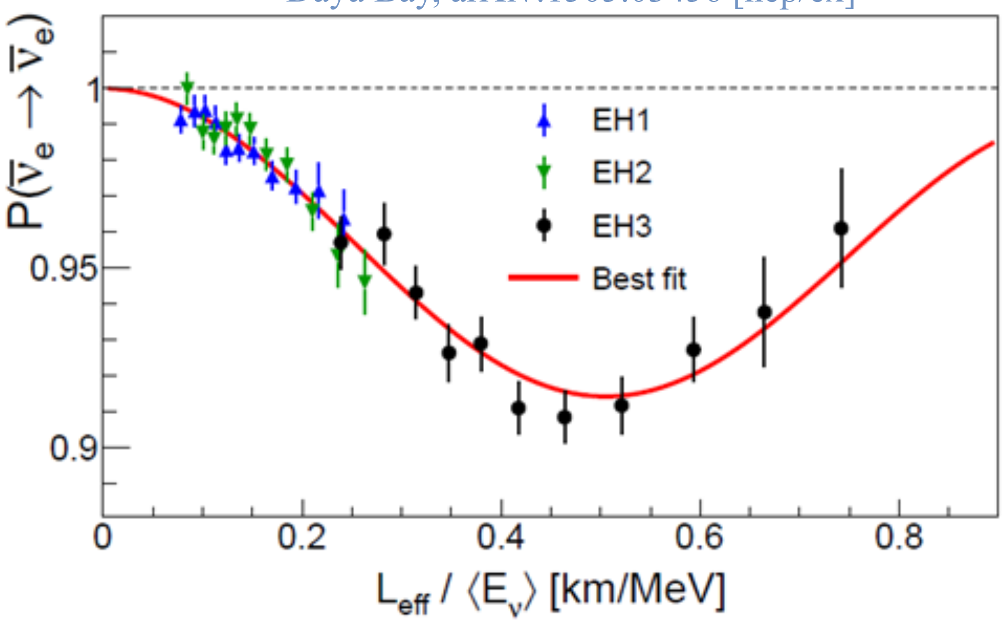
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

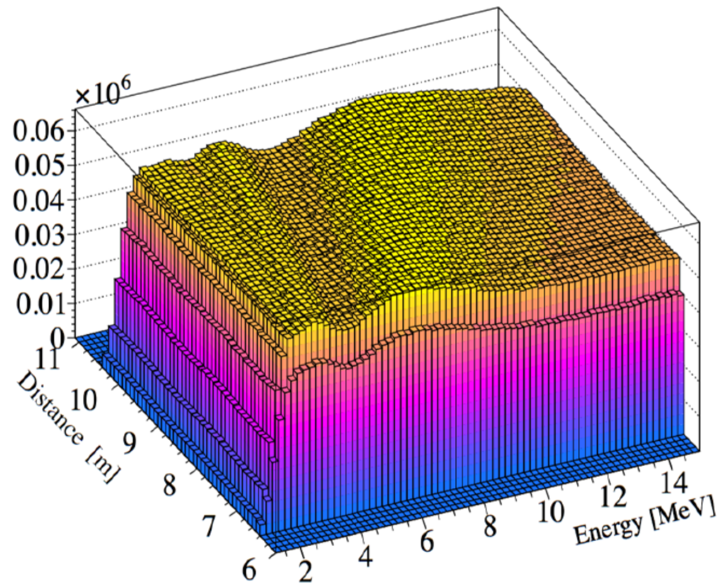
Definition:

oscillometry, *n.*, The observation and measurement of oscillations.

Daya Bay, arXiv:1505.03456 [hep/ex]



Possible oscillations in a short-baseline reactor experiment



In disappearance experiments the existence of sterile neutrinos can ***only*** be convincingly established through oscillometry.

The Two Types of Disappearance Experiments

Radioactive Source Experiments: the source is brought to a pre-exiting detector

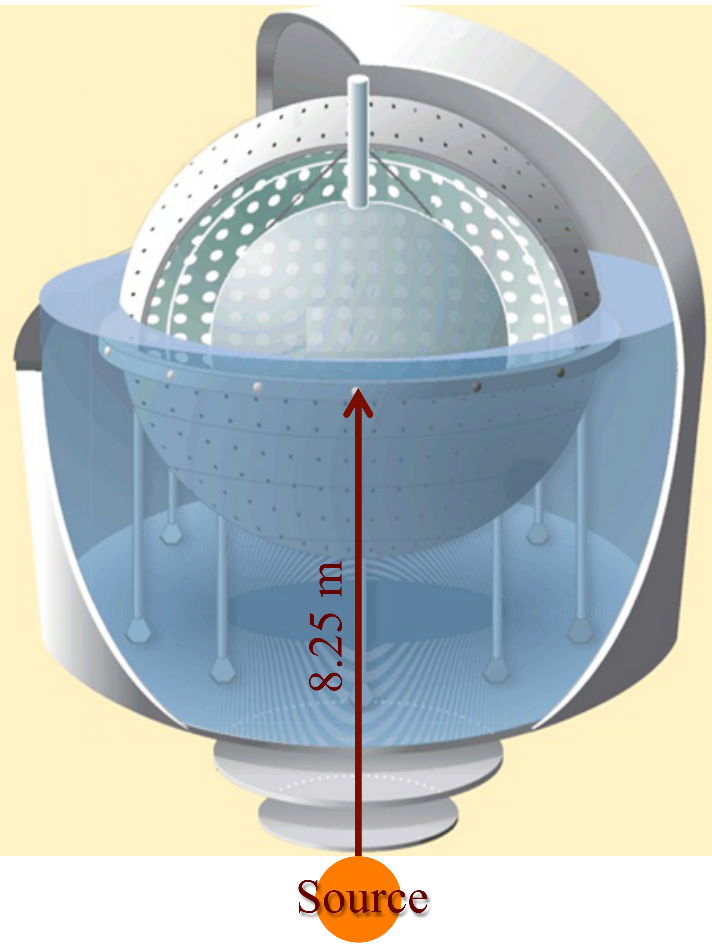
1. Leverages detectors built for other applications (*e.g.* solar neutrinos, dark matter).
2. Often these detectors have existing analysis, well measured backgrounds and a well understood energy response.
3. The source decays away, so to accumulate additional statistics requires a new investment on the scale of the original deployment.

Reactor Experiments:

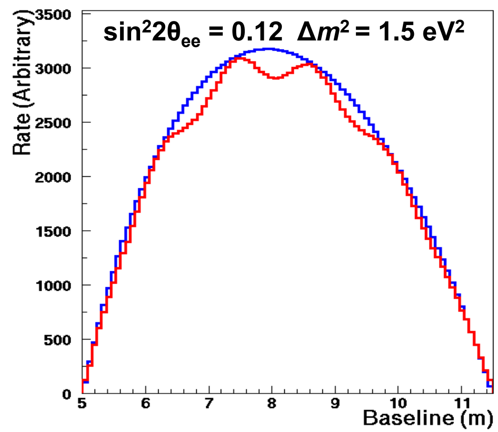
Source Experiment: SOX

Combines the Borexino detector with a ^{144}Ce ν_e source and/or a ^{51}Cr ν_e source.

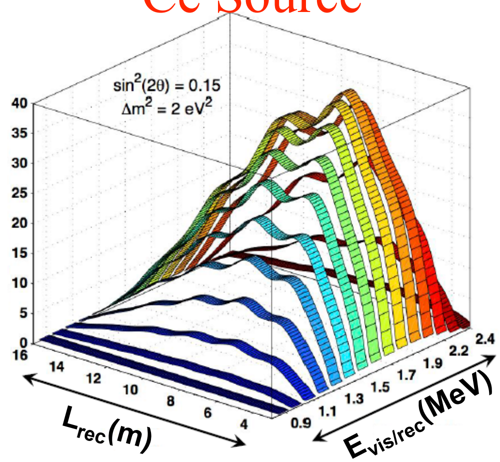
At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

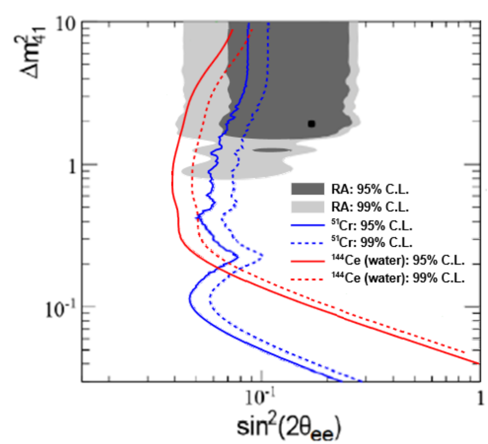


^{51}Cr Source



^{144}Ce Source





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2. Often these detectors have existing analysis, well measured backgrounds and a well understood energy response.
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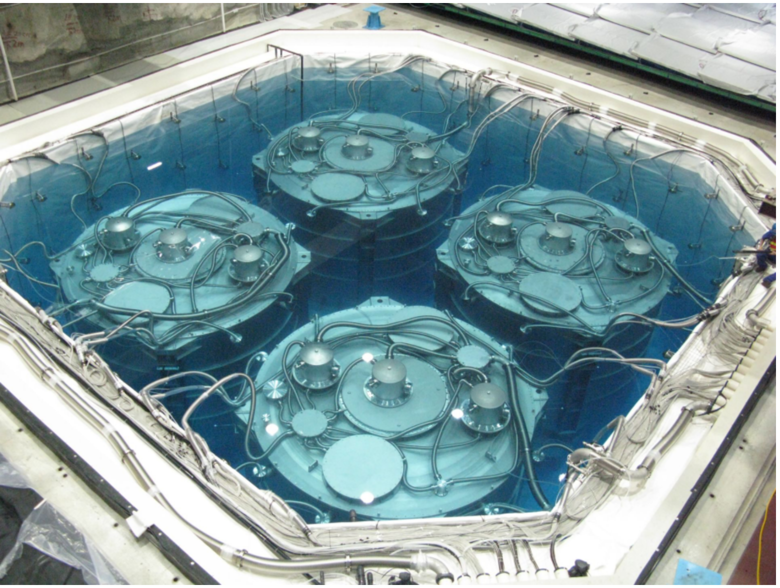
Reactor Experiments: the detector is brought to a pre-existing source

1. Nuclear reactors are the most prolific terrestrial neutrino sources, producing 6×10^{17} $\nu \downarrow e$ per second per MW_{th}.
2. It is unlikely that a reactor would ever be constructed specifically for use as a neutrino source, nevertheless, neutrino experiments can use existing reactors without any impact on their normal operations.
3. Once the detector has been delivered, neutrino statistics accumulate with minimal operational costs.

Reactor Experiments



The Daya Bay Far Detectors

In the Daya Bay reactor experiment the mixing amplitude, $\sin^2 2\theta_{13}$ has been measured to an absolute precision of 0.5%.

Extraordinary measures were taken to control backgrounds: deep underground detectors are imbedded in meters of low-activity water shielding instrumented as a muon detector.

Short-baseline reactor experiments must be done at the surface, with limited space for shielding.

In Daya Bay the oscillation was initially detected as a deficit in detectors at the far site relative to detectors nearer to the reactor cores.

In order to demonstrate the existence of sterile neutrinos, short-baseline reactor experiments must detect the oscillatory pattern as a function of energy and distance in one or more detectors located at baselines of 5 to 15 meters from a reactor core.

Keys to a Short-Baseline Reactor Experiment

1. Sensitivity to the higher Δm^2 range (2 eV^2 and above) requires a compact reactor core and good energy resolution.

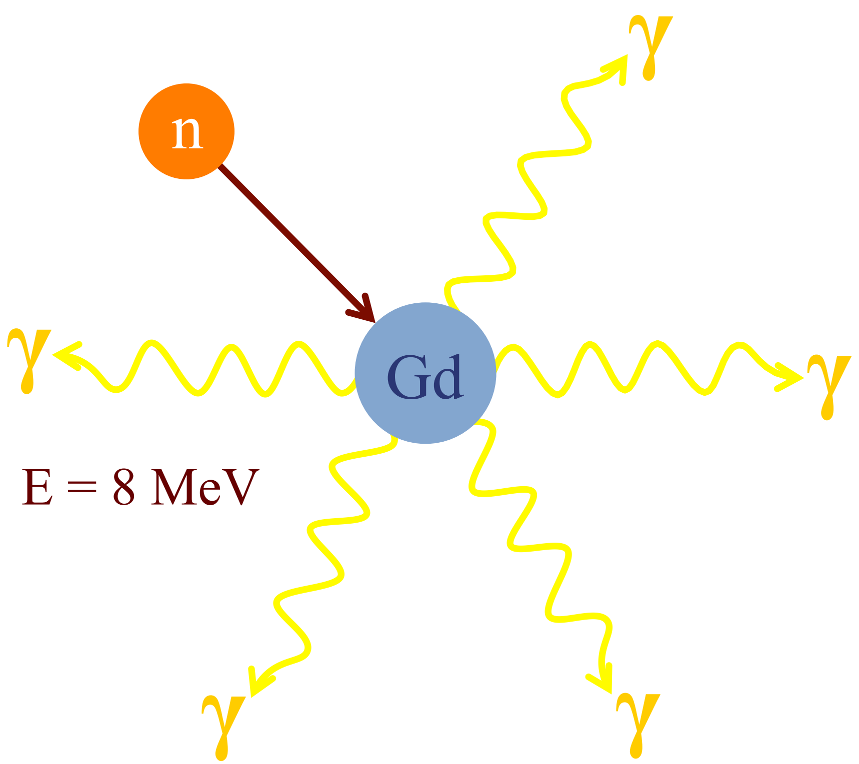
2. Relatively small detectors require careful consideration of isotope used for neutron capture and tagging.

Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons by Gd capture. All three experiments use a large gamma catcher, outside the Gd-doped volume to contain the gammas.

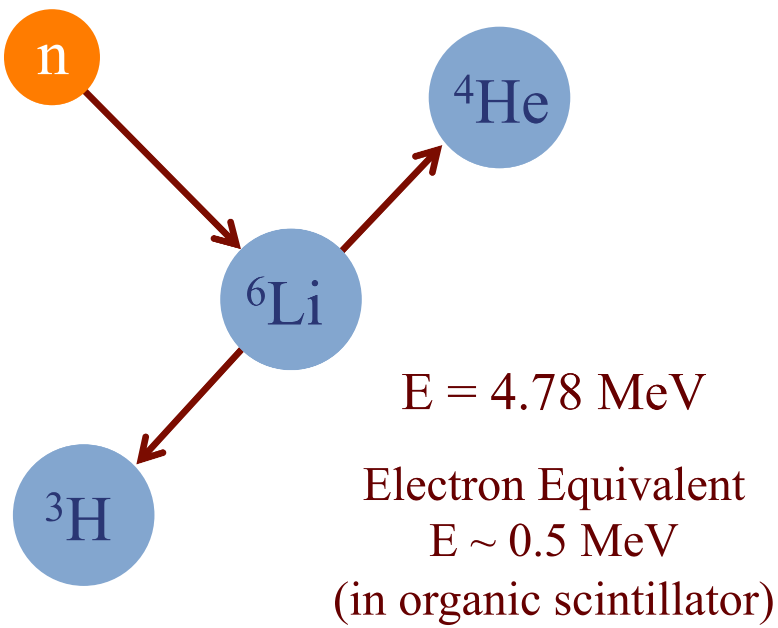
This will not work well in the much smaller short-baseline detectors.

Neutron Capture on Gadolinium



Poorly contained in small detectors

Neutron Capture on Lithium-6



Contained in a few micrometers

Keys to a Short-Baseline Reactor Experiment

1. Sensitivity to the higher Δm^2 range (2 eV^2 and above) requires a compact reactor core and good energy resolution.

2. Relatively small detectors require careful consideration of isotope used for neutron capture and tagging.

3. Backgrounds, particularly from random coincidences are the most significant challenge.

   Random coincident backgrounds can be reduced by:

   a. Reducing background rates (shielding)
   b. Improving signal pattern recognition, and
   c. Tightening coincidence criteria

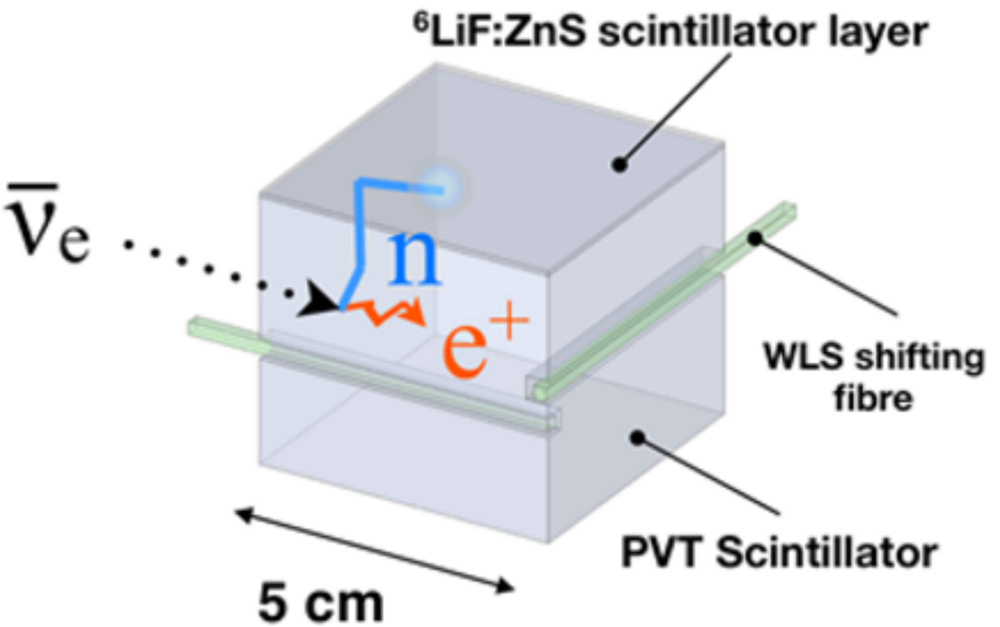
SoLid: Tagging with ^{6}Li in ZnS:Ag Sheets

The SoLid detector tags neutrons in thin sheets of ^{6}Li-loaded, silver activated zinc sulfide scintillator: 6LiF:ZnS(Ag).

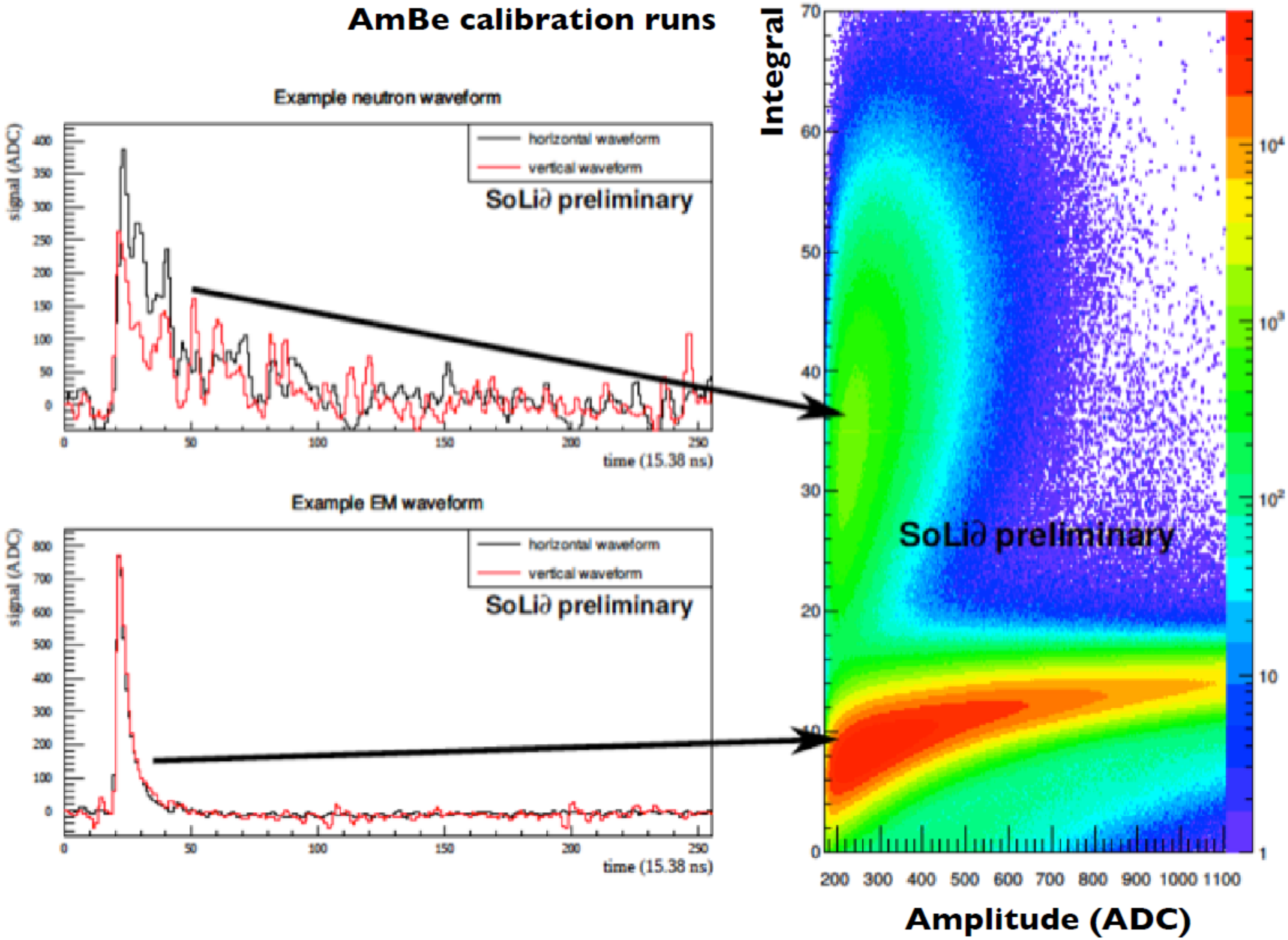
ZnS(Ag) releases light with a 200 ns mean emission time which forms a very pure, high efficiency neutron tag.

SoLid achieves unprecedented spatial resolution by segmenting its scintillator in cubes which are readout in two dimensions by wavelength shifting fibers.

The fiber readout is inefficient at light collection and limits the energy resolution.



The SoLid Signal

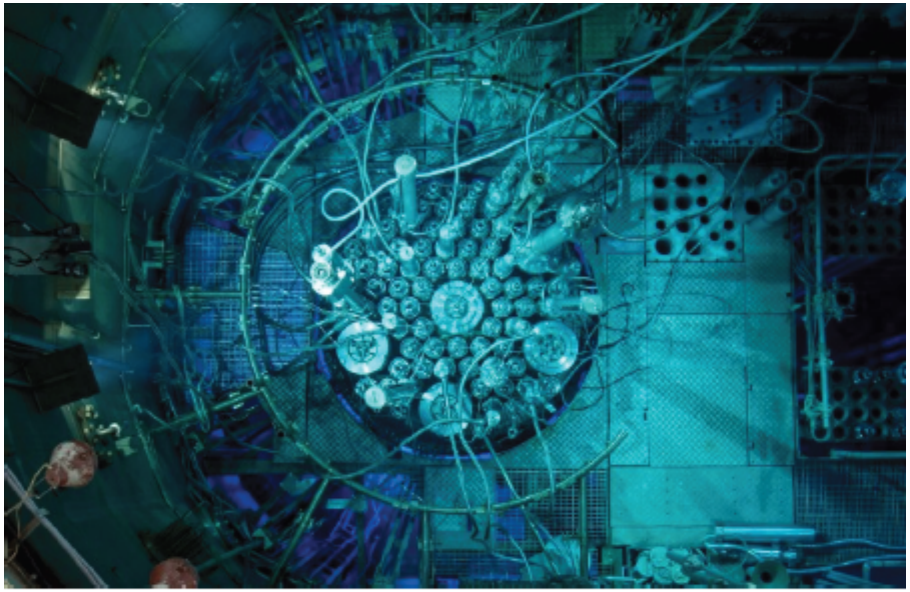


The BR2 Reactor

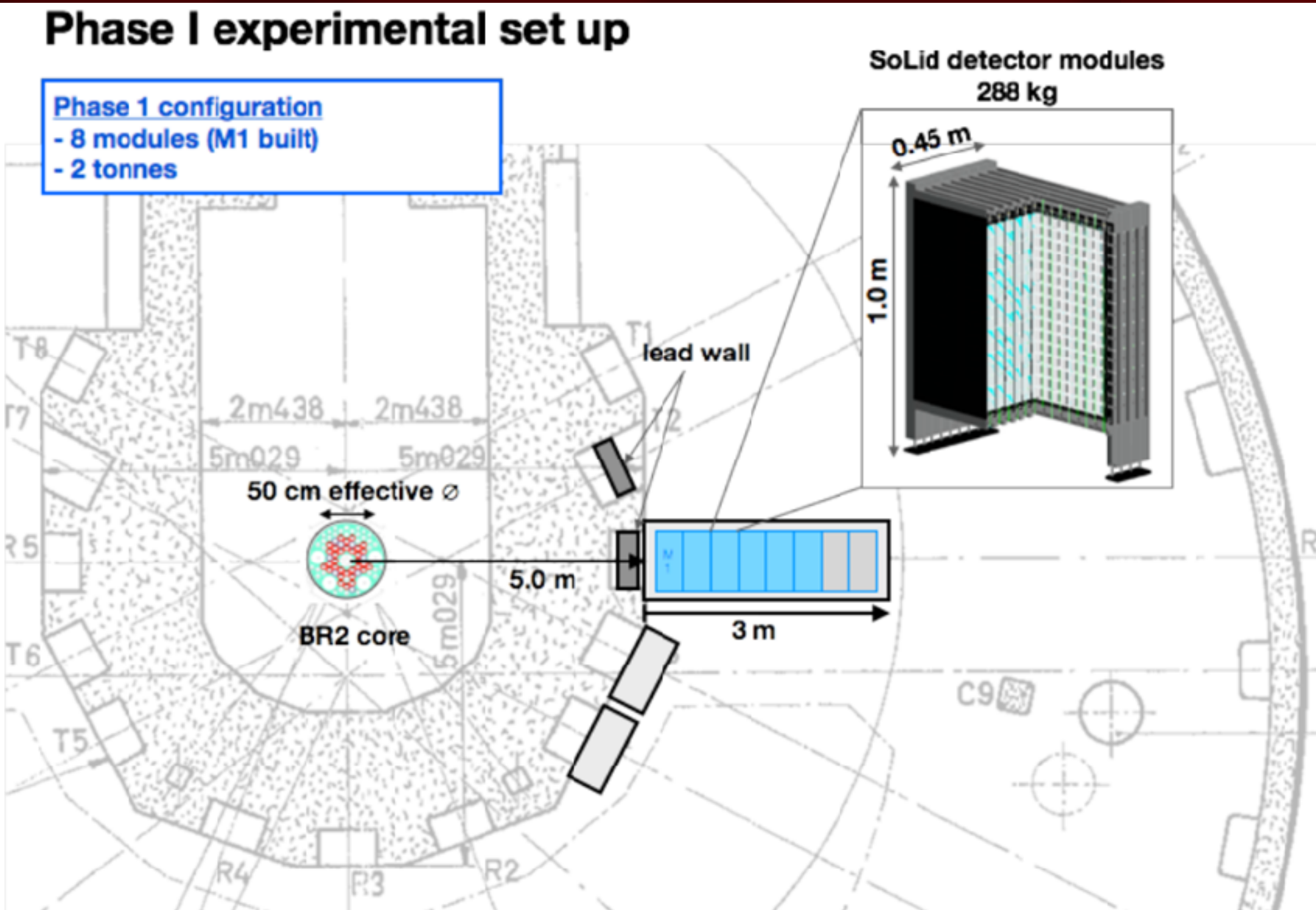
The 60 MW BR2 reactor is a facility at the Belgian National Nuclear Lab, SCK•CEN.

With a 5.5 meter closet approach this site has the highest reactor antineutrino flux of any publically knowable compact reactor site.

The absence of any beam portals makes for a relatively low-background site with backgrounds dominated by the typical environmental sources.



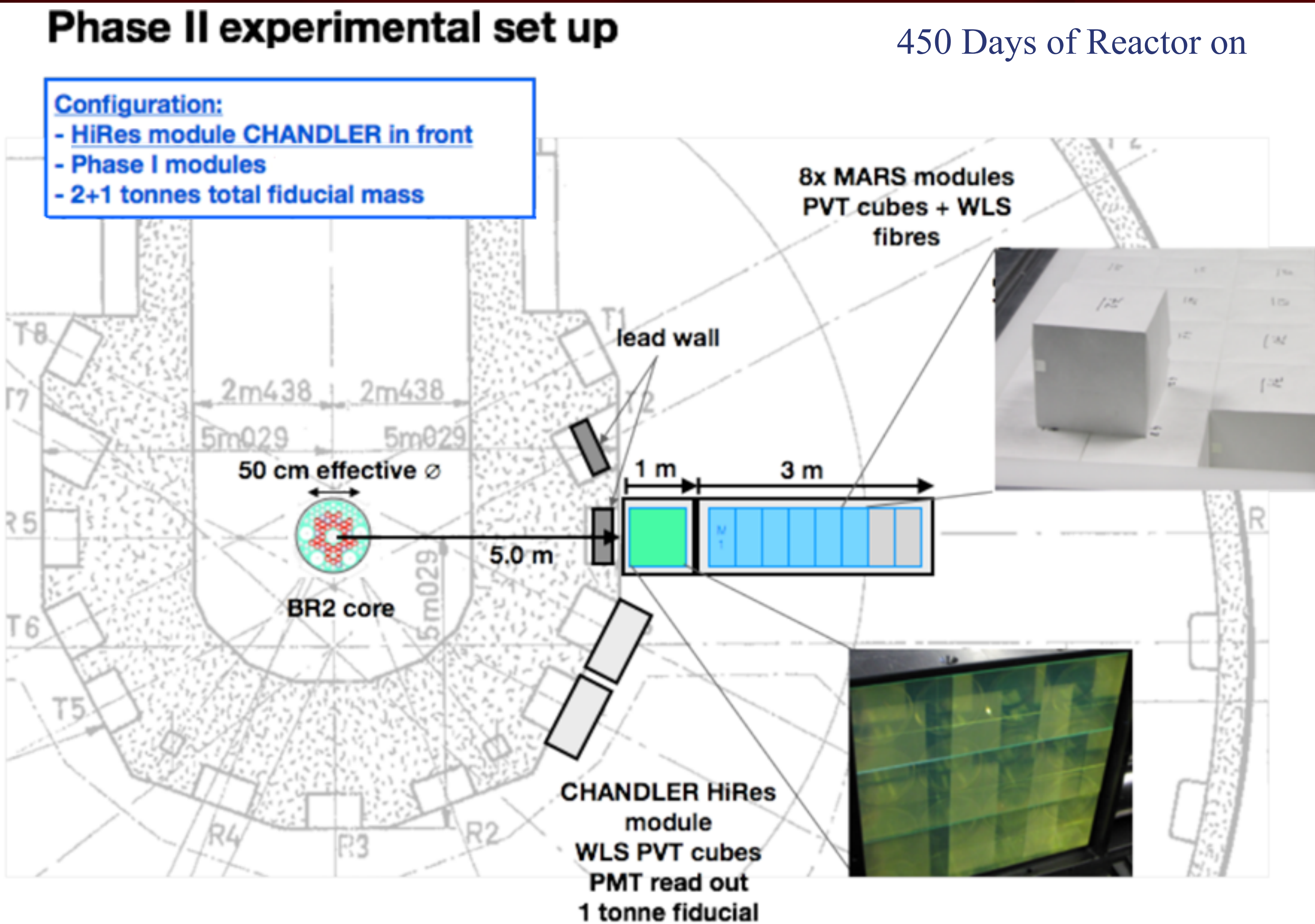
SoLid at the BR2 Reactor in Belgium



150 Days of Reactor on

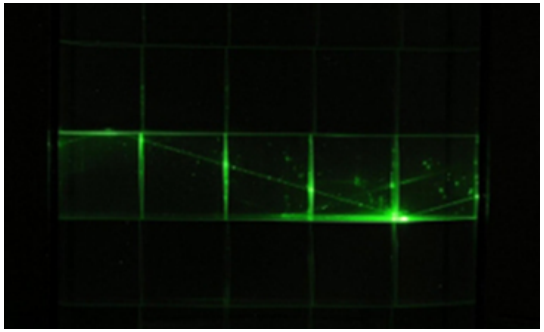
SoLid at the BR2 Reactor in Belgium

450 Days of Reactor on



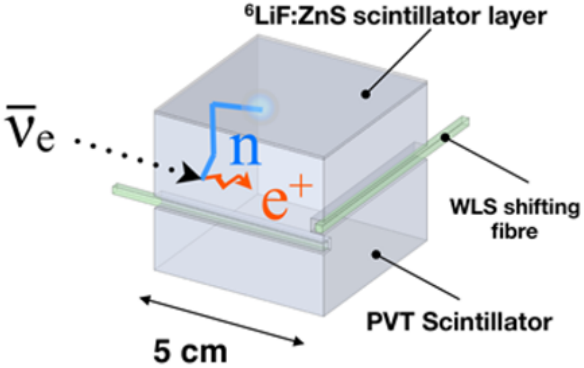
Technological Convergence

LENS



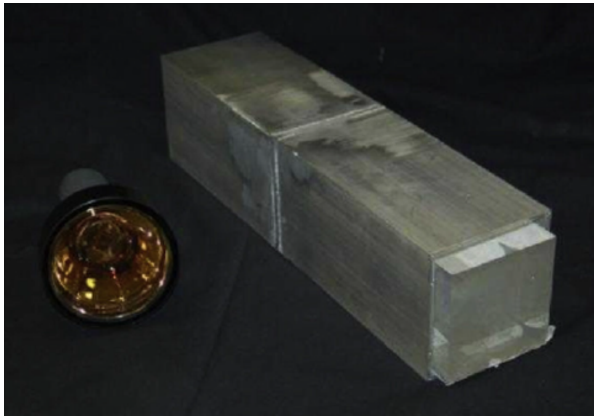
The **Raghavan Optical Lattice** (ROL), invented by the late Virginia Tech professor, Raju Ragahvan, divides a totally active volume into cubical cells that are read-out by total internal reflection. LENS was designed for solar neutrino detection and not optimized for reactor antineutrino detection.

SoLid



Optically isolated cubes, mated to **^{6}LiF:ZnS(Ag) sheets**, are used to tag IBD. Light is read-out by wavelength shifting fibers in orthogonal directions. It has the spatial resolution of the ROL optimized for reactor antineutrino detection. The small cross-sectional area of the fibers limits the light collection, dilutes the energy resolution and lowers the efficiency.

Sweany et al., NIMA 769, 37

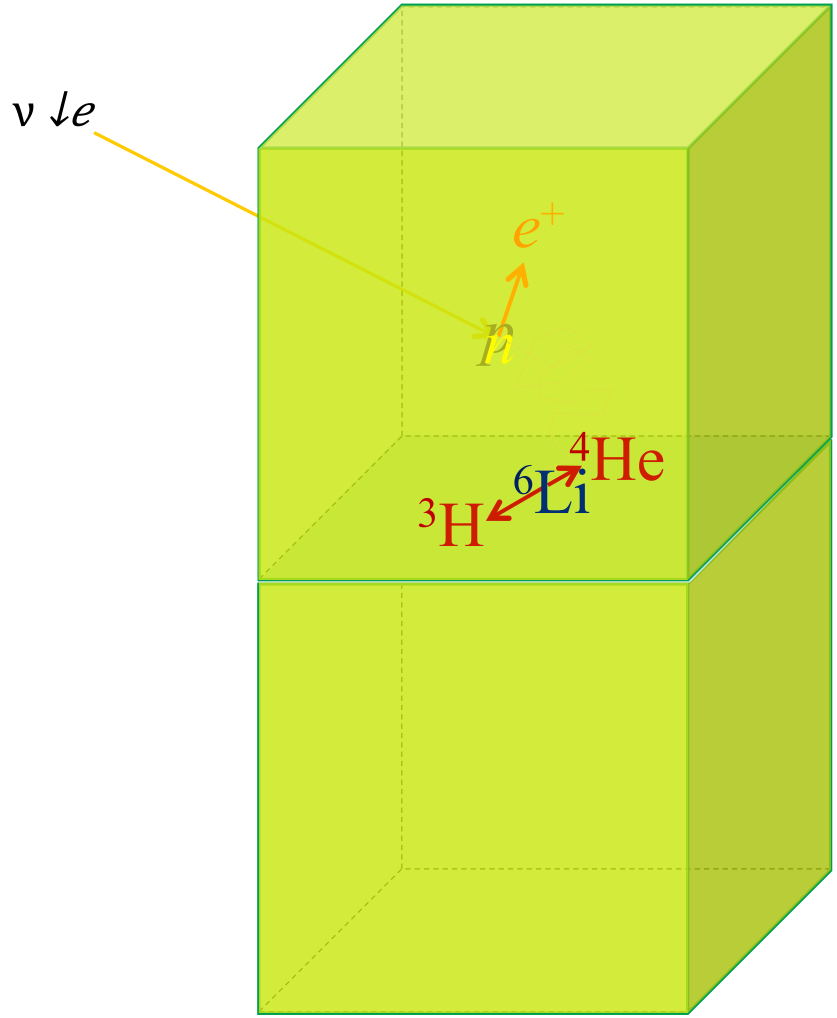


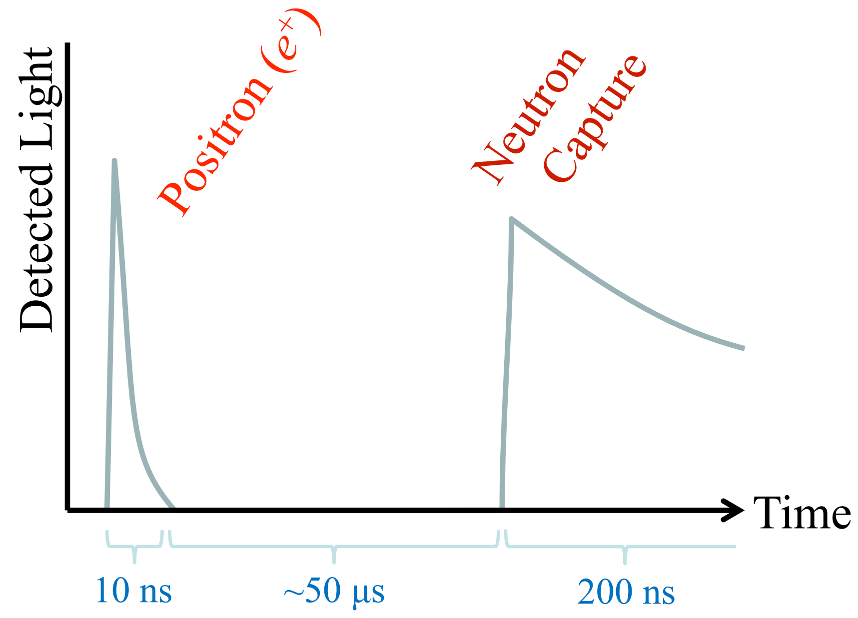
Used ^{6}LiF:ZnS(Ag) sheets mated to a **solid bar of wavelength-shifting plastic scintillator**. This prototype demonstrated the feasibility of pairing the sheets to wavelength shifting plastic, but the long bars do not have the spatial resolution required for good background rejection

CHANDLER

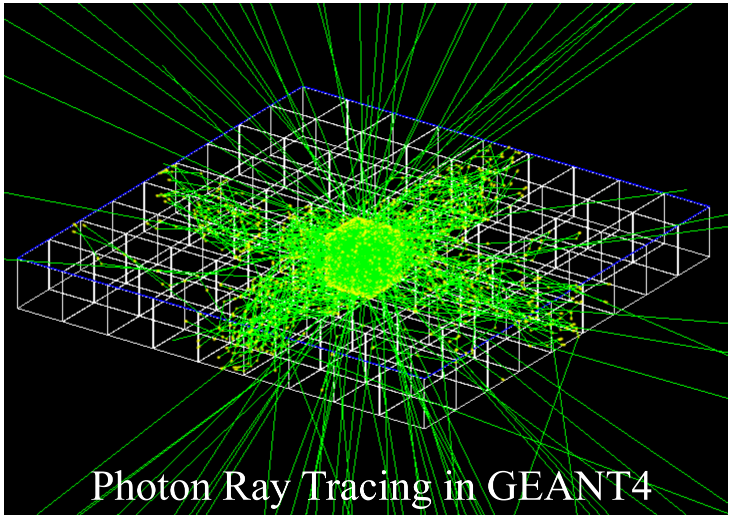
Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

The CHANDLER Detector

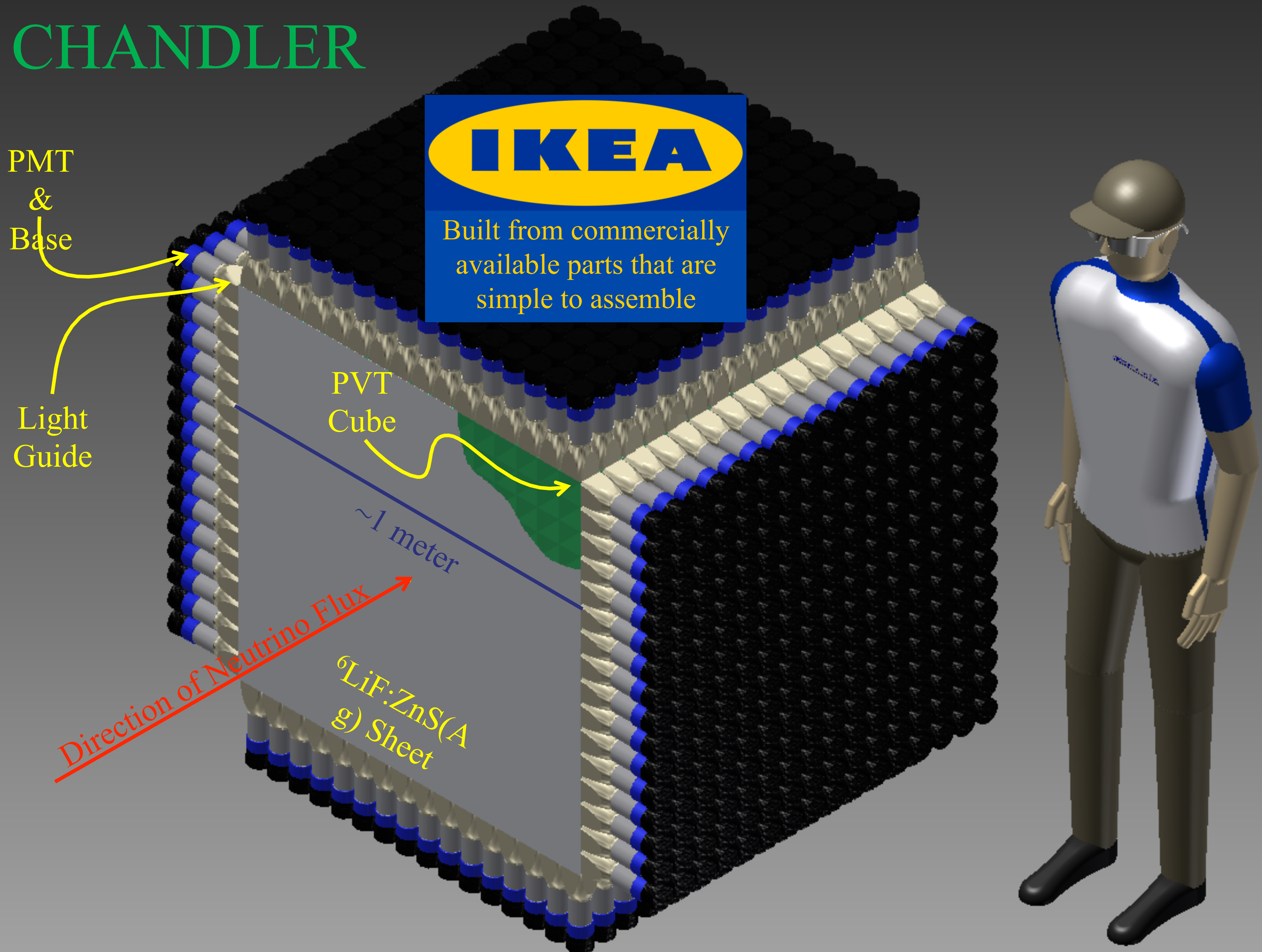




Light is transported by total-internal-reflection



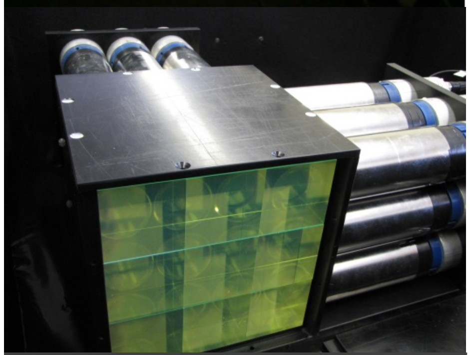
CHANDLER



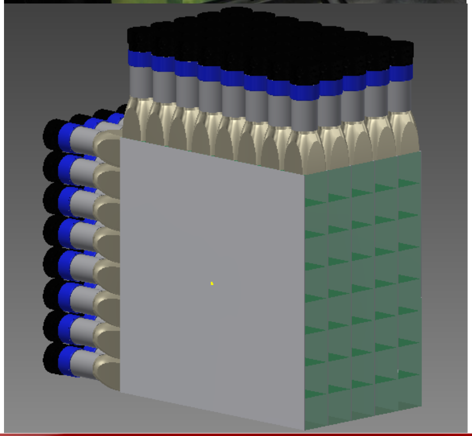
IKEA
Built from commercially available parts that are simple to assemble
PMT & Base
Light Guide
PVT Cube
~1 meter
Direction of Neutrino Flux
^{6}LiF:ZnS(Ag) Sheet

Research and Development Effort

<u>Cube String Studies</u> have been used to study light production, light collection, light attenuation, energy resolution and wavelength shifter concentration.

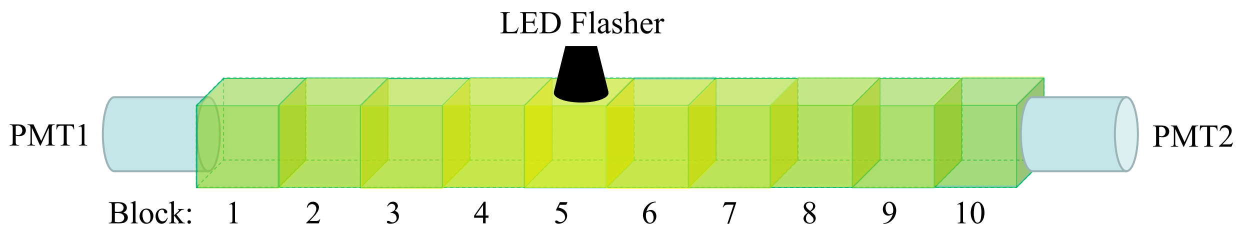


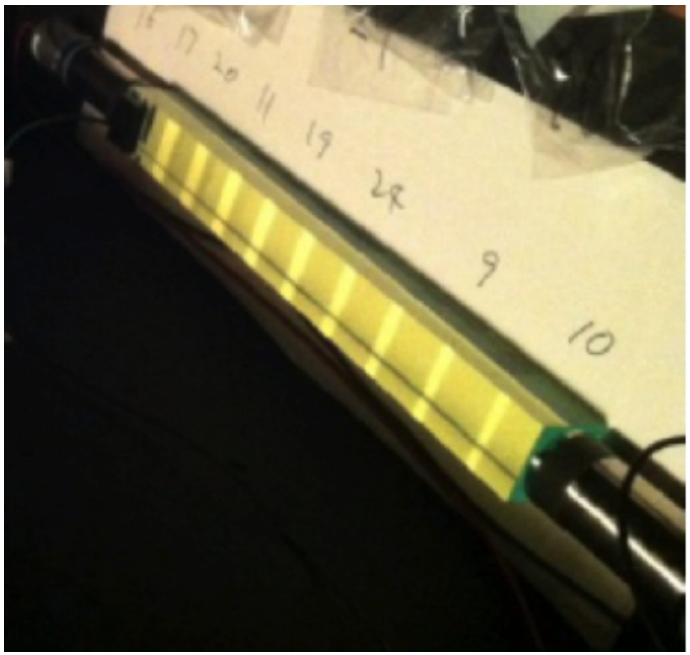
<u>MicroCHANDLER</u> is a 3×3×3 prototype which we are using to test our full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.

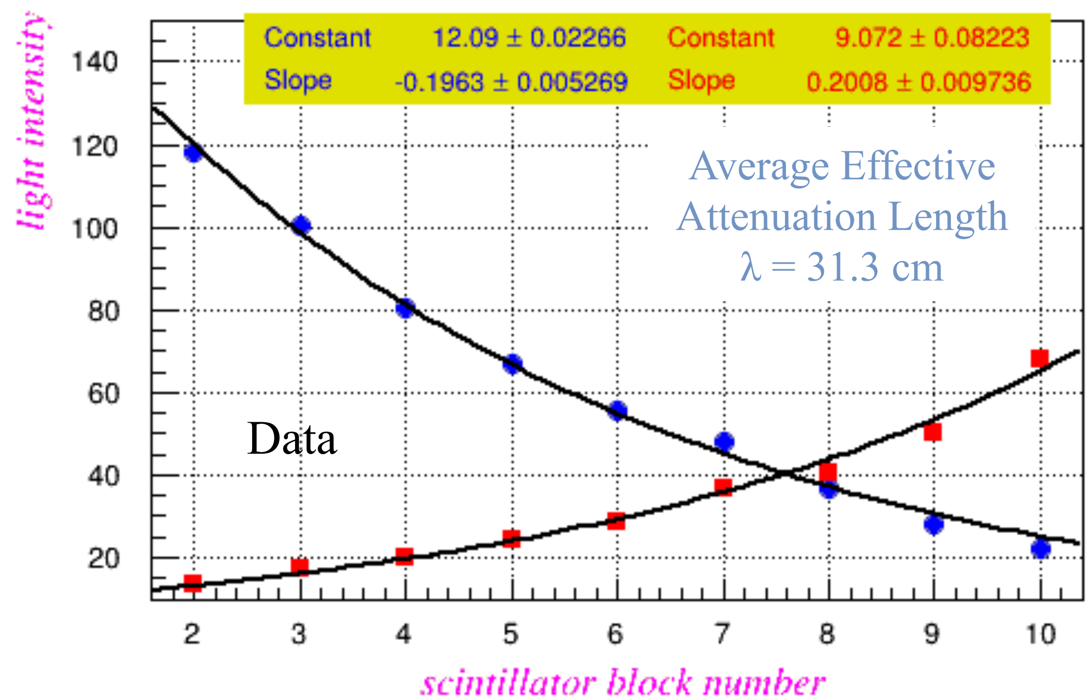


<u>MiniCHANDLER</u> is a **fully funded** systems test (8×8×5) which is currently under construction which will be deployed at a commercial nuclear power plant. It will be used to test any remaining options and optimizations. It will be operational by spring 2016.

Effective Attenuation Length Study



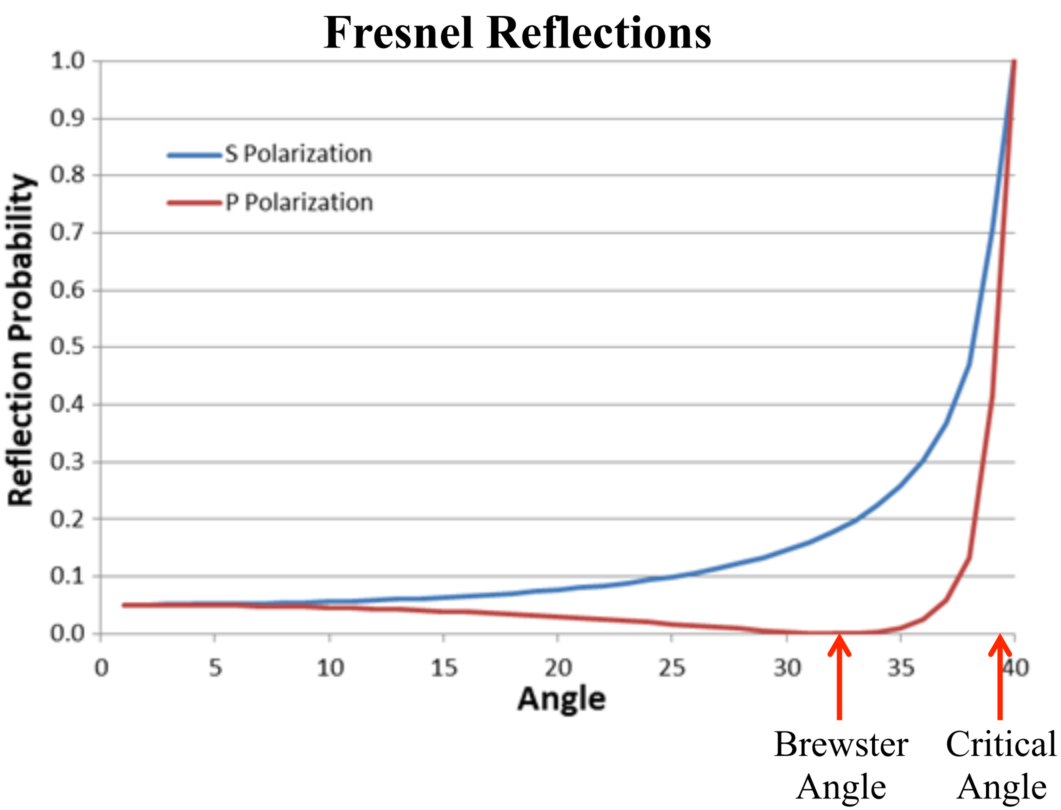




There are two contributions to the effective attenuation:

1) bulk attenuation in the PVT and
2) Fresnel reflection at the cube interfaces.

Optics of the Raghavan Optical Lattice



The optics are based on the interface of PVT (n=1.58) and air (n=1).

The critical angle (θ_c) is 39.27°

The Brewster angle is 32.22°

Because $\theta_c < 45°$ any light capable of passing between cubes will necessarily fall into the total-internal-reflection (TIR) channel in that direction.

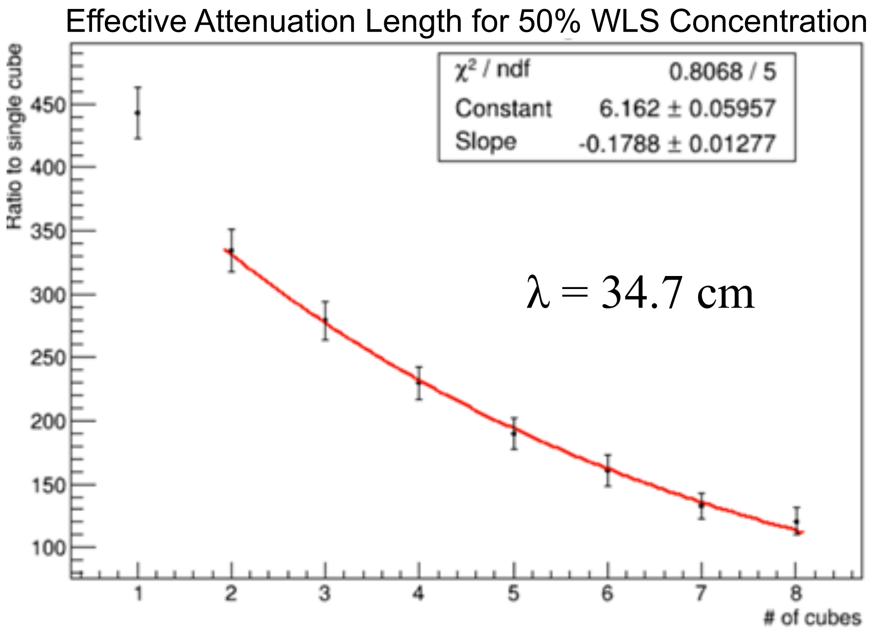
Each of the four TIR channels is open to 11.3% of the light produced in a cube.

54.8% of all light can not be channeled.

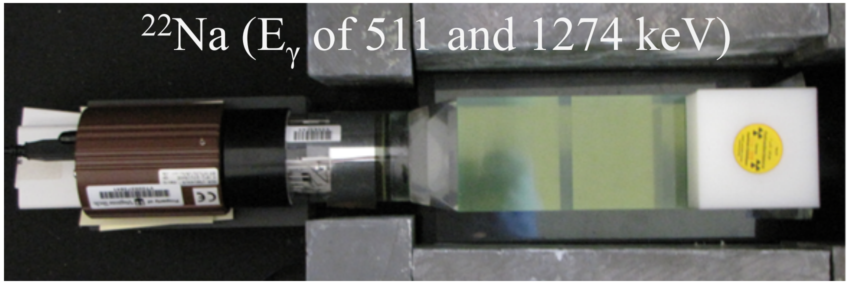
Some channeled light that gets reflected off of a cube surface perpendicular to the channel direction will reach the PMT in the opposite direction.

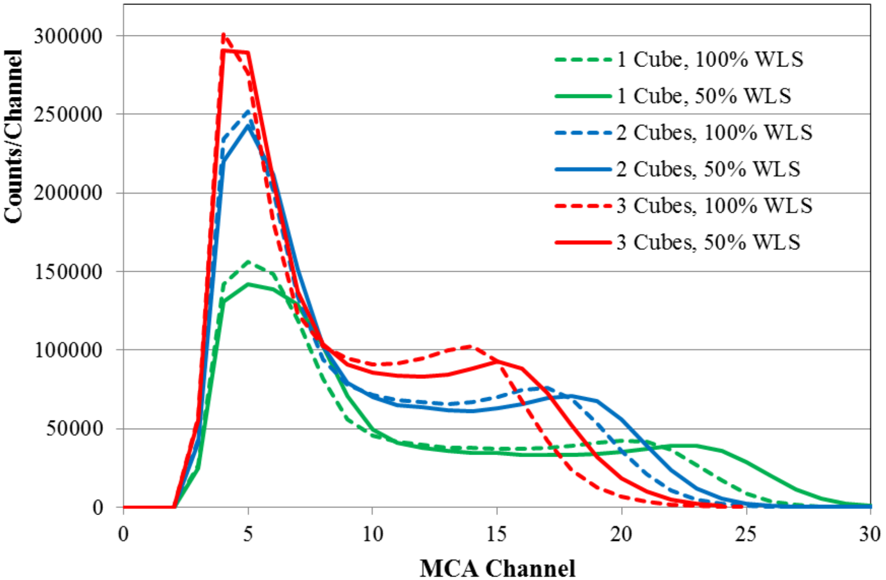
Wavelength Shifter Concentration

The wavelength shifter (WLS) dopant can be a significant source of attenuation.



The Compton edge of ^{22}Na was used to study the relative light output.



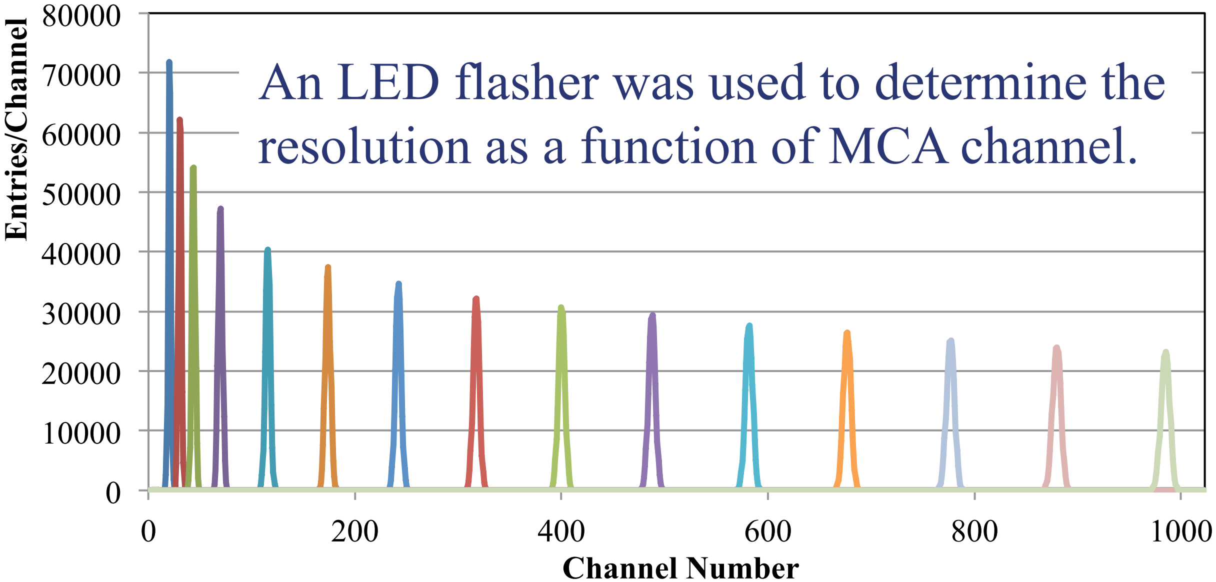


Halving the WLS concentration increases the attenuation length by 10%.

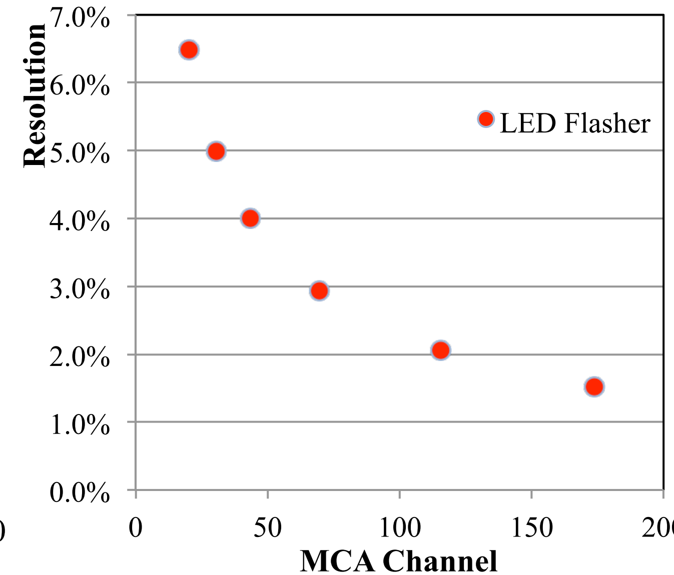
The light collection with lower WLS is greater at each position.

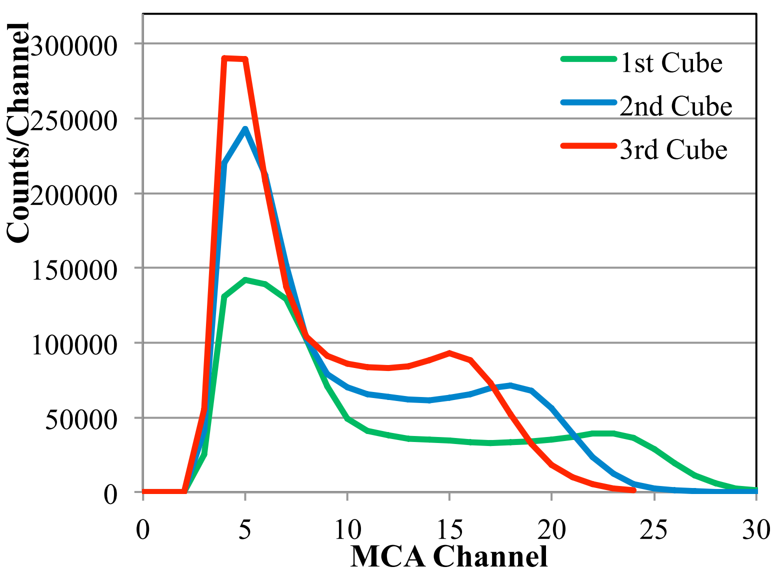
We will also be studying WLS concentrations of 75% and 25%.

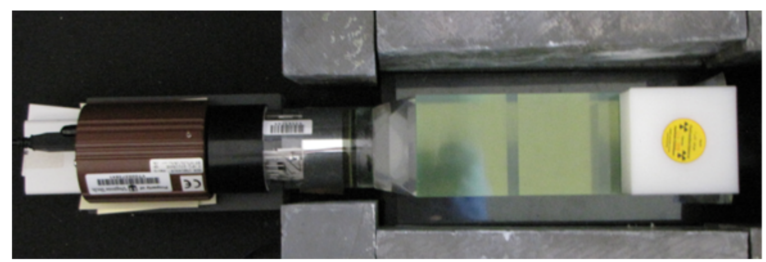
Light Output and Collection



An LED flasher was used to determine the resolution as a function of MCA channel.





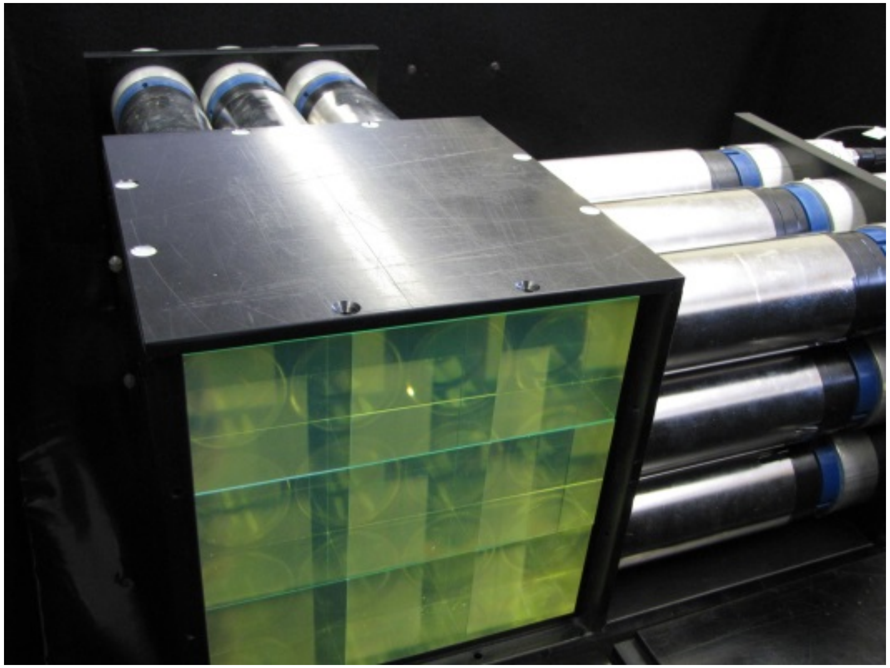


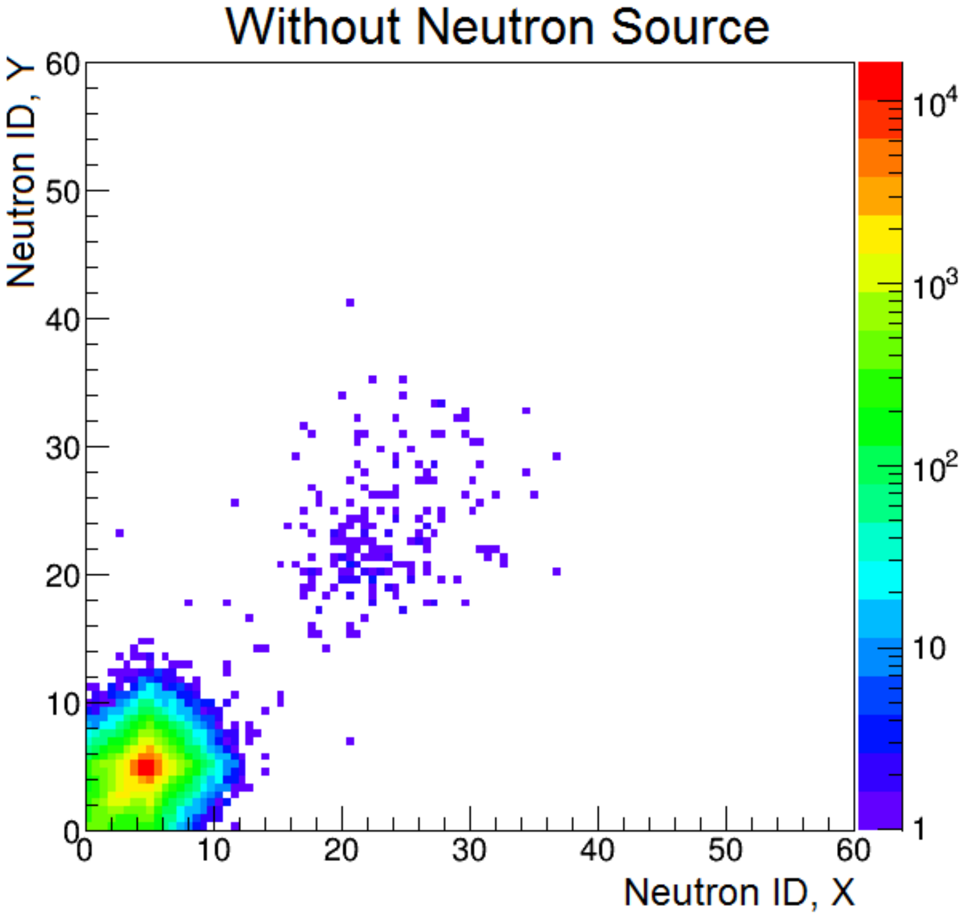
The ^{22}Na Compton edge is at 1.06 MeV, and at two cubes from the PMT it reconstructs at channel 20, which corresponds to an energy resolution of 6.5%.

Neutron Capture in MicroCHANDLER

The 18-channel MicroCHANDLER prototype is idea for testing neutron tagging.

For each hit cell, we compute the neutron ID variable as the ratio of the integral of the pulse to the pulse peak value.



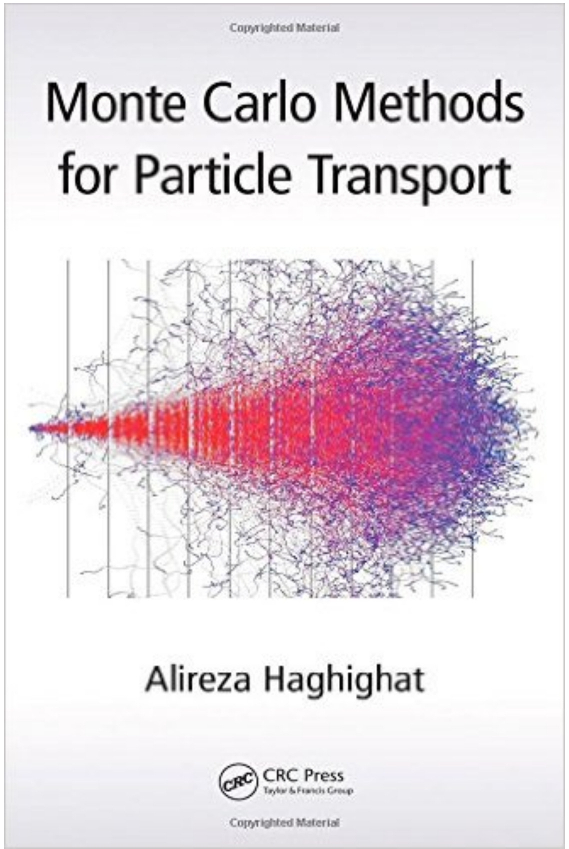


Detector Simulation

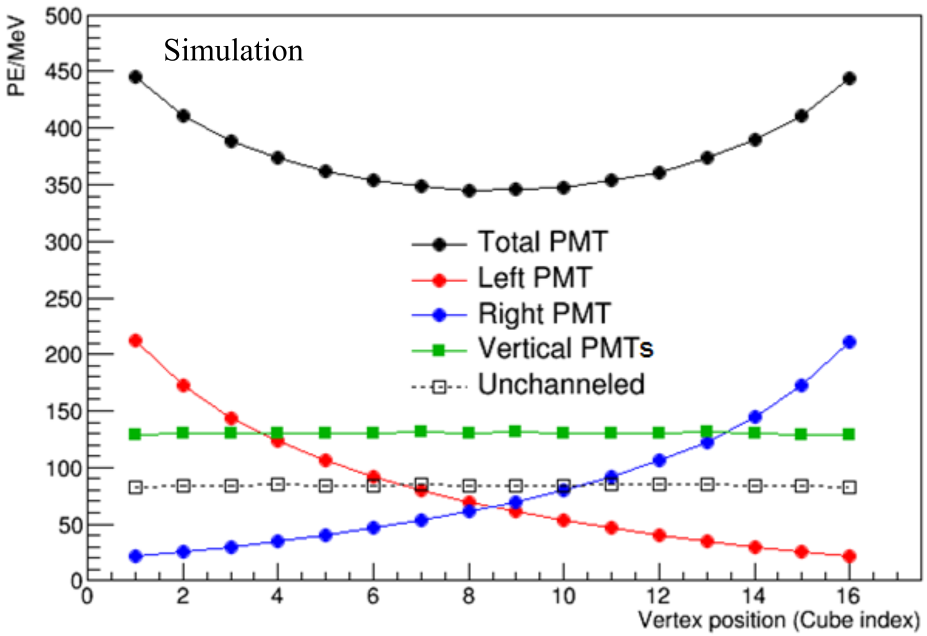
We have a full-scale GEANT4 simulation, developed by Jaewon Park, which we are using to study light transport and collection, and neutron transport and capture.

We also have a full-scale MCNP6 simulation, developed by William Walters and Alireza Haghighat, which we are using to study neutron transport and capture.

The neutron transport models in GEANT4 and MCNP6 are in very good agreement.



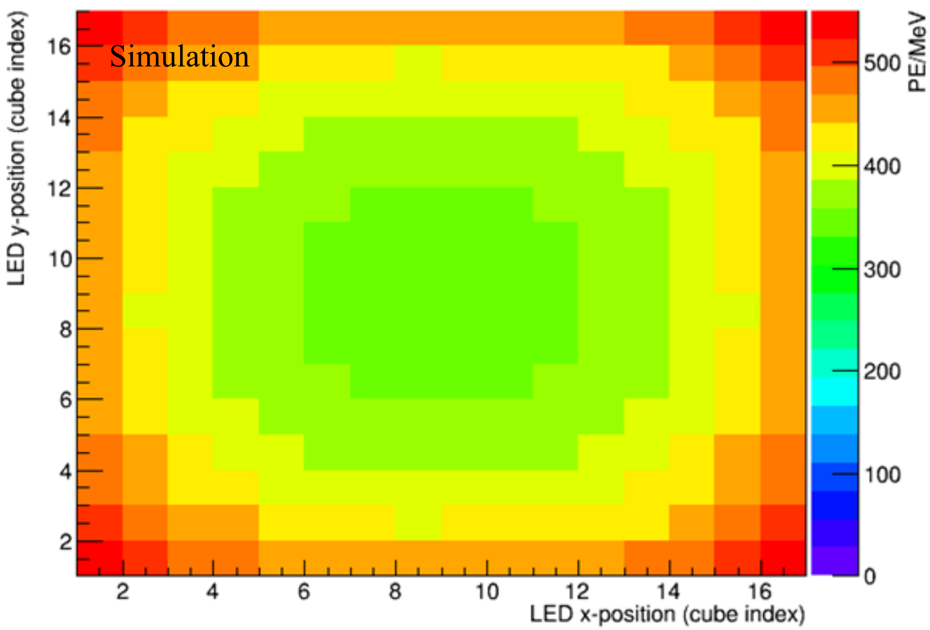
GEANT4: Detector Response vs. Cube Position



Most of the light is collected in the 4 PMTs in the TIR channel directions.

About 20% of light is unchanneled, with the largest share in the adjacent PMTs.

Collected light falls off as you move away from the PMT.

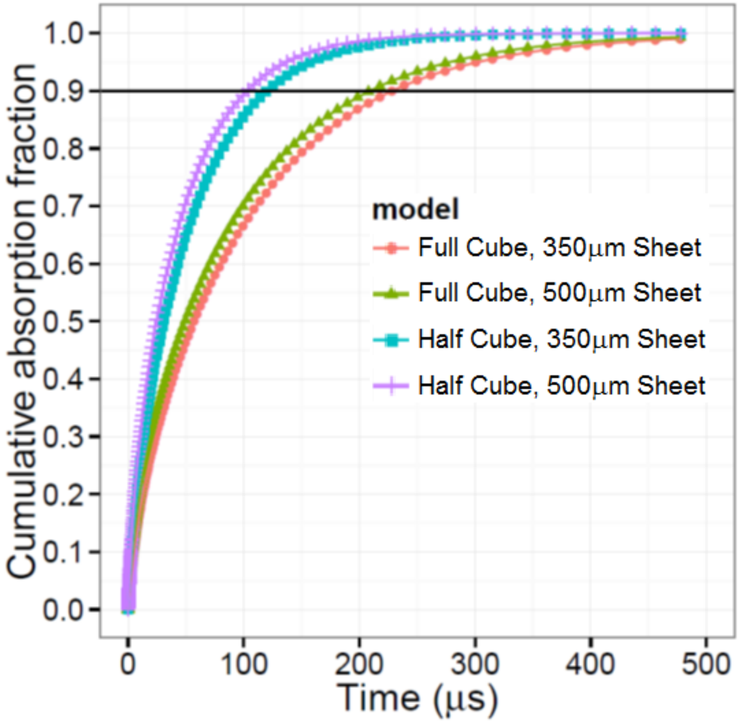


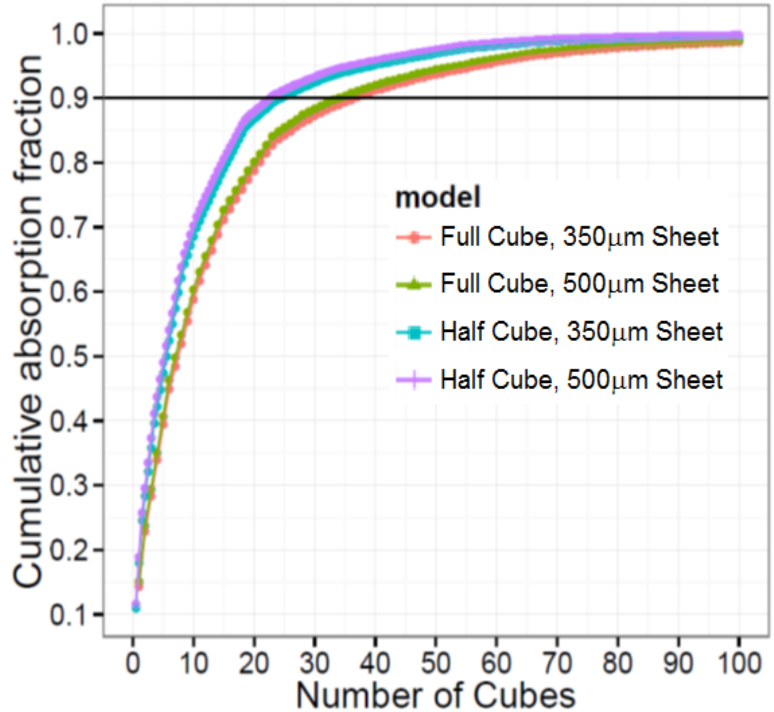
The largest excursion from the mean is in the corner cells.

The conversion to p.e./MeV assumes light guides, and a PMT maximum quantum efficiency of 25%.

MCNP6: Neutron Transport and Capture

	^{6}Li Capture	Time to 90% Capture	Volume for 90% Capture
Full Cube, 350 μm Sheet	51%	229 μs	37 cubes
Full Cube, 500 μm Sheet	55%	209 μs	35 cubes
Half Cube, 350 μm Sheet	69%	120 μs	24.5 cubes
Half Cube, 500 μm Sheet	73%	103 μs	23 cubes





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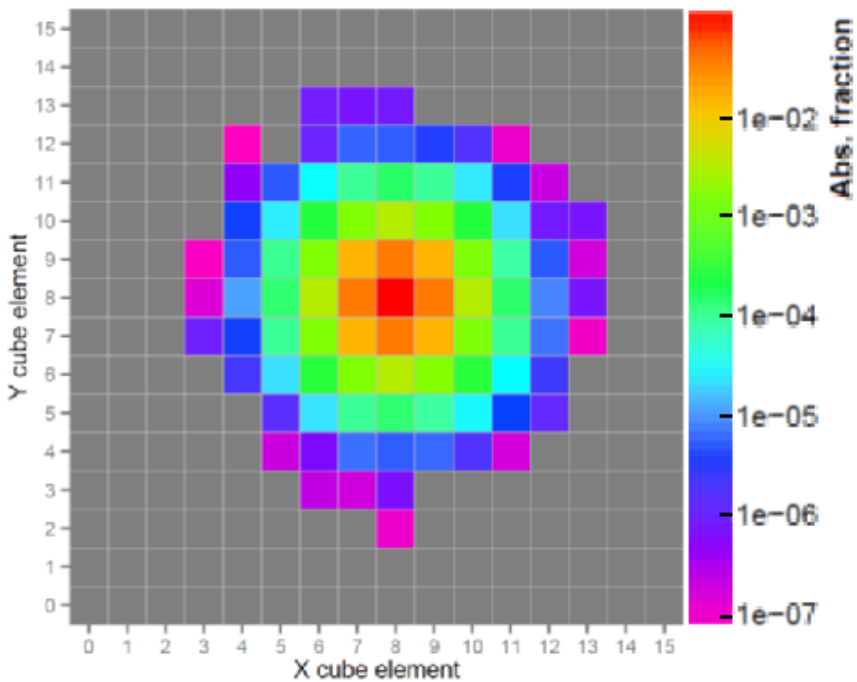
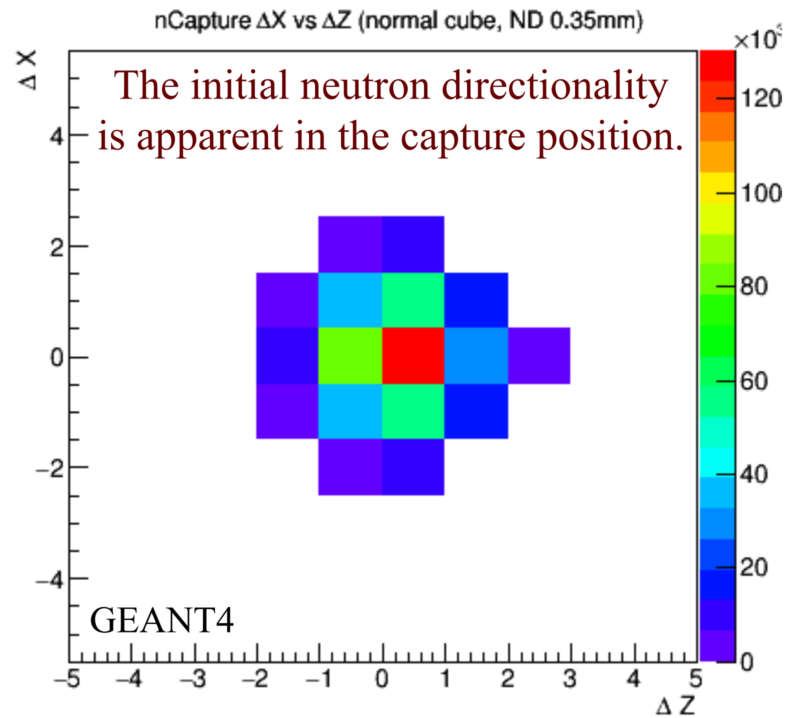
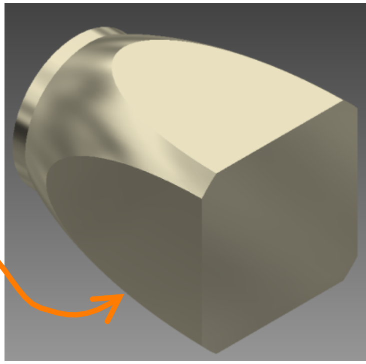




Next Steps in R&D Program…

MiniCHANDLER parts acquisition is almost done:

- 350 cubes and 6 sheets delivered
- 100 two-inch Amprex PMTs found in the department basement.
- Testing the prototype compound parabolic light concentrator (should increase light by 60%)



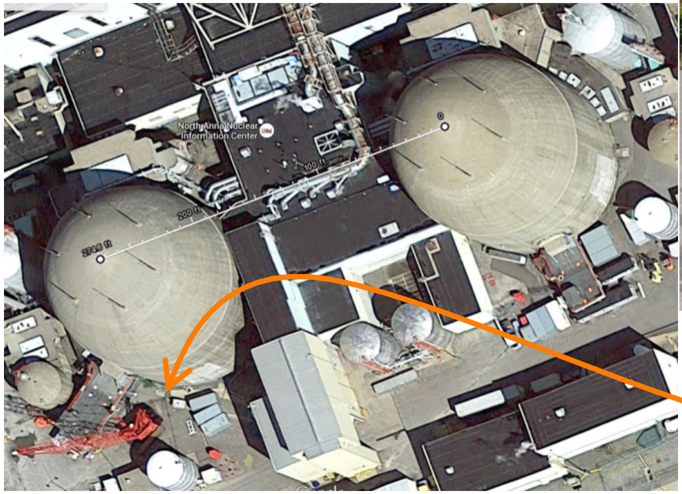
Engineer Jan Boissevain is working on the mechanical support structure

We are rebuilding MicroCHANDLER to test design features

Purchase and outfit a mobile neutrino lab

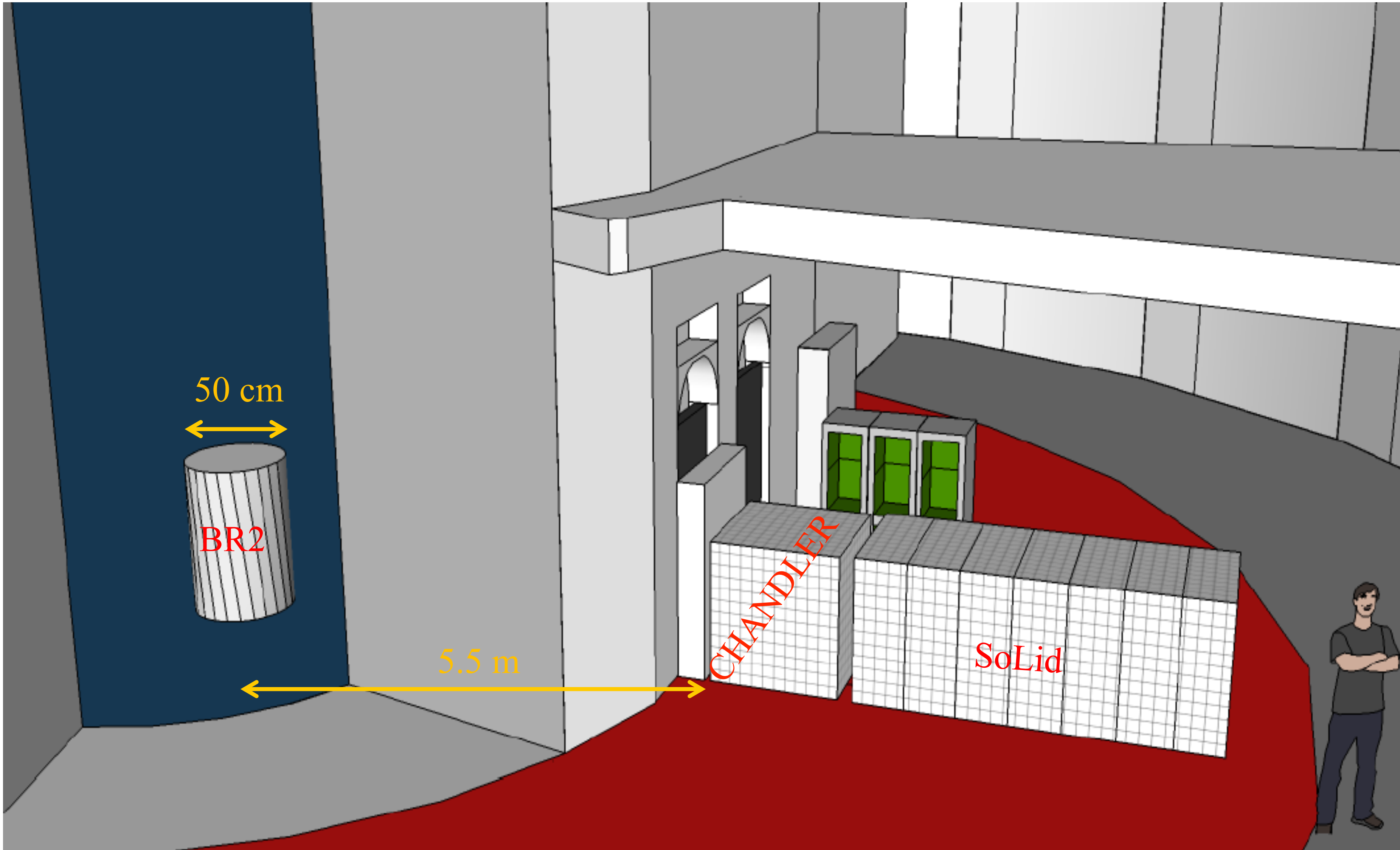
Deploy lab and detector at the North Anna Nuclear Power Station

Expect about 100 events/day



CHANDLER and SoLid

The two detectors will be deployed at the BR2 reactor operating as a single experiment.



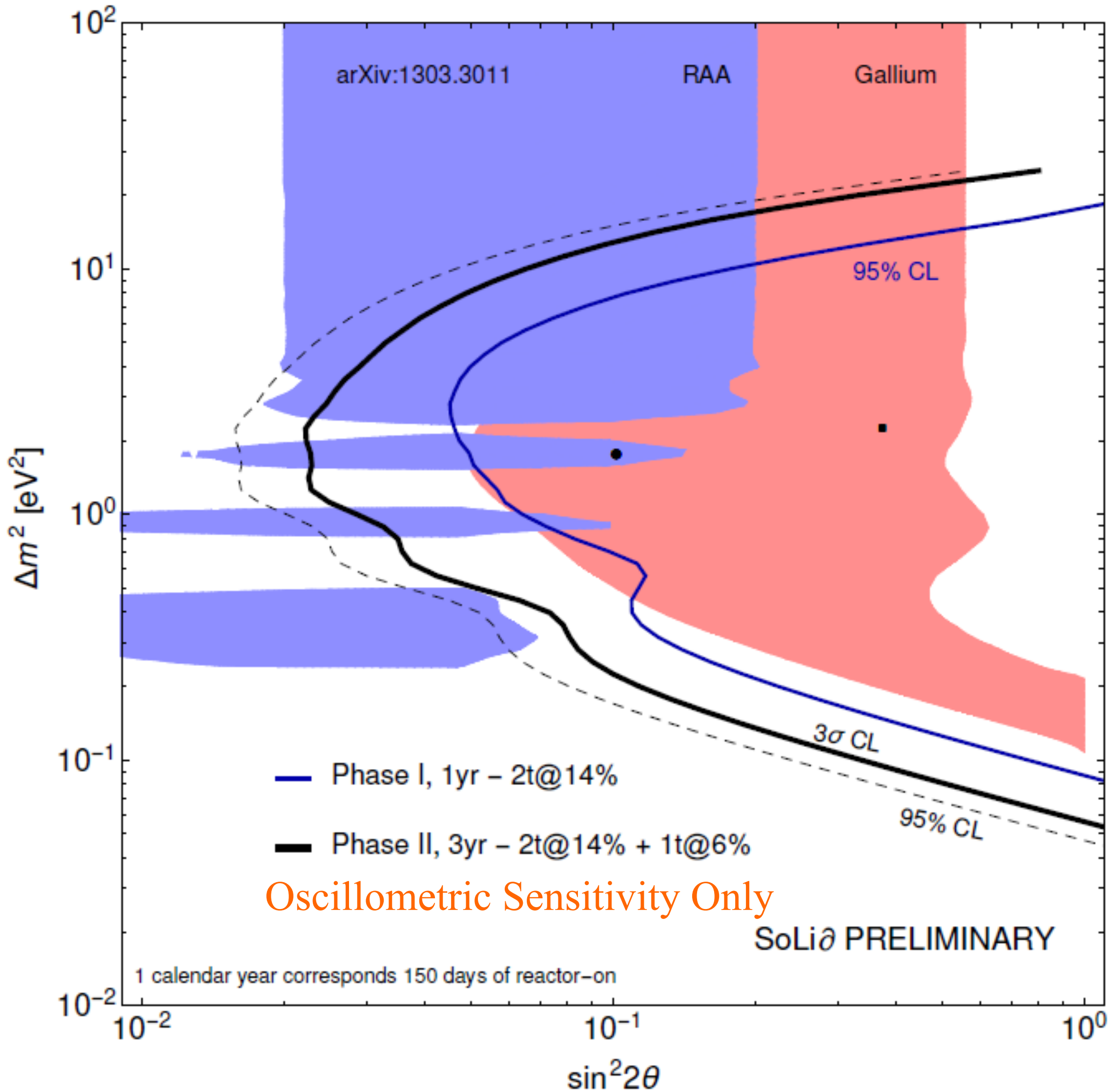
SoLid and CHANDLER Sensitivity

The combined sensitivity for the SoLid/CHANDLER deployment at BR2 is compared to the Gallium and Reactor Anomalies.

The one-year, Phase I SoLid deployment covers most of the low Δm^2 part of the Gallium Anomaly at 95% CL.

Adding CHANDLER to the three-year Phase II extends the coverage to higher Δm^2 and pushes the reach well into the Reactor Anomaly.

These sensitivities are purely oscillometric, based on energy spectrum and baseline information alone.



Application to Nuclear Non-Proliferation

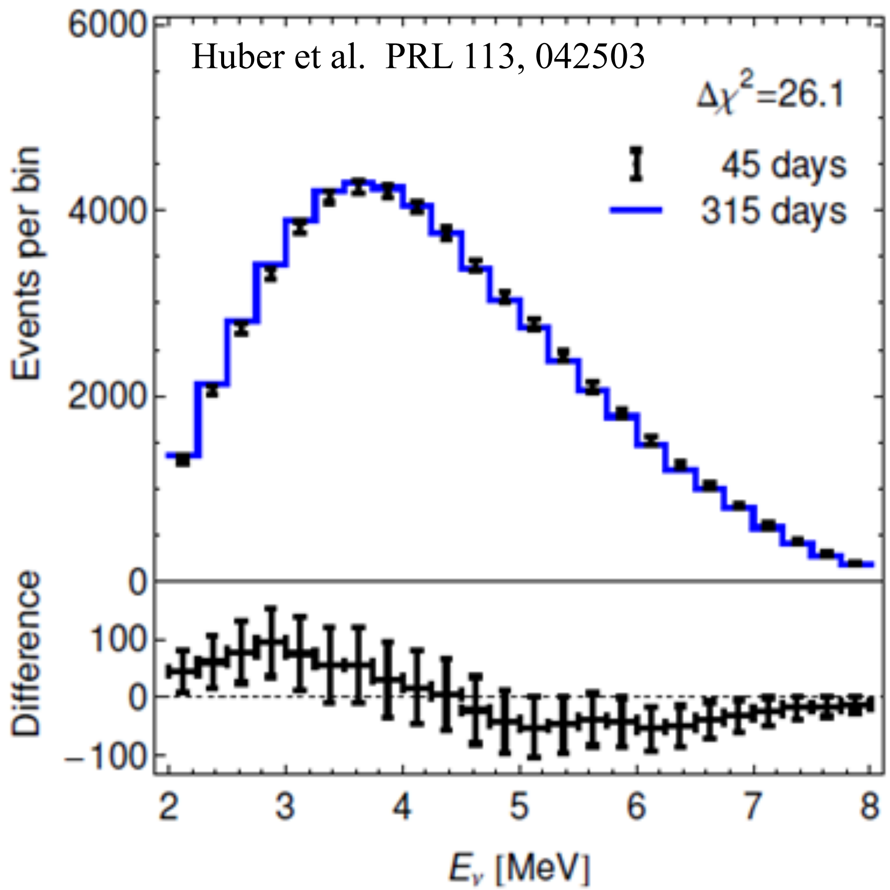
Neutrino monitoring has been proposed as a **non-invasive** verification scheme to be used in nuclear treaties with nations such as Iran and North Korea. This possibility is currently under study by the IAEA and the US Departments of State and Energy.

The basic idea is to look for changes in the neutrino energy spectrum indicative of diversions of weapons grade plutonium.

The main stumbling block to the full embrace of neutrino safeguards has been the inability to demonstrate a viable detector technology.

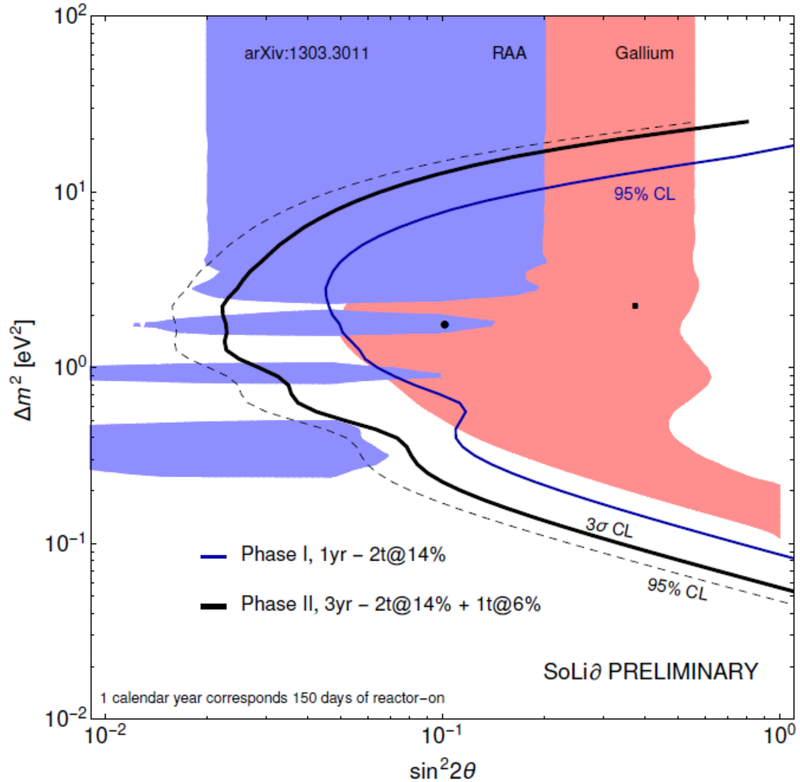
Safeguards detectors must:

- be portable, reliable and low-cost;
- have good energy resolution;
- and be free of potential hazards such as flammable liquids (this requirement comes from the IAEA).



Conclusions

1. The evidence for a 1 eV^2 sterile neutrino is persistence but inconclusive.
2. Electron neutrino disappearance, which must exist if any of the oscillation hints are true, is the most promising way to resolve the sterile neutrino question.
3. Radioactive source and reactor neutrino experiments will soon be operating to search for short-baseline oscillations.
4. CHANDLER is a new detector technology with high purity, high efficiency neutron tag and good energy resolution.
5. Together CHANDLER and SoLid cover most of the ν_e disappearance allowed space.

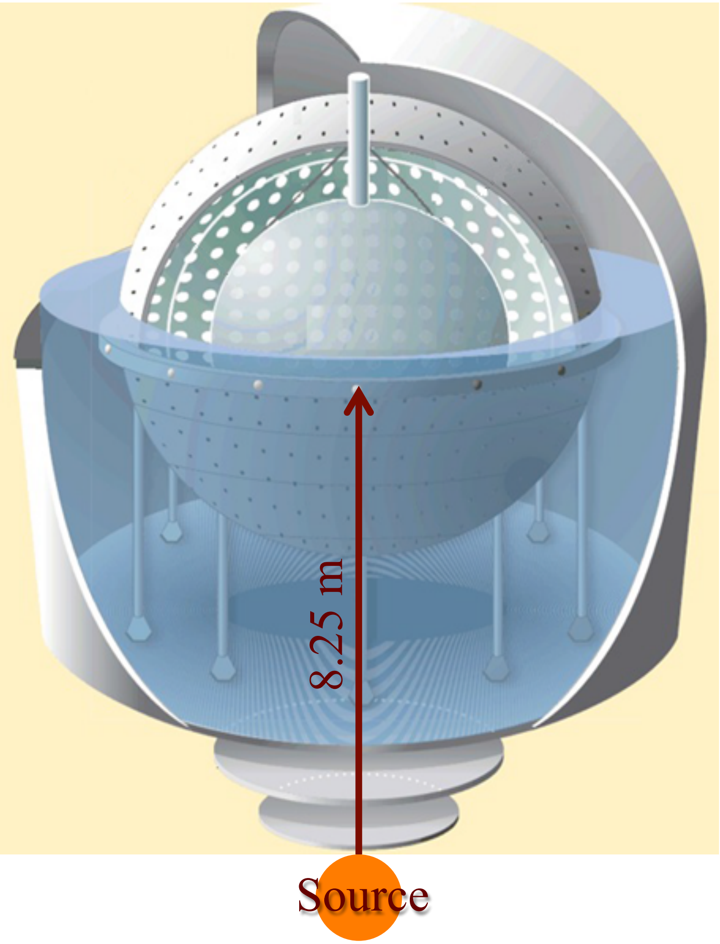


Source Experiment: SOX

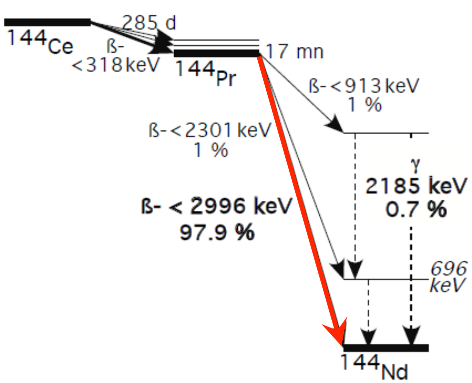
Combines the Borexino detector with a ^{144}Ce ν↓e source and/or a ^{51}Cr ν↓e source.

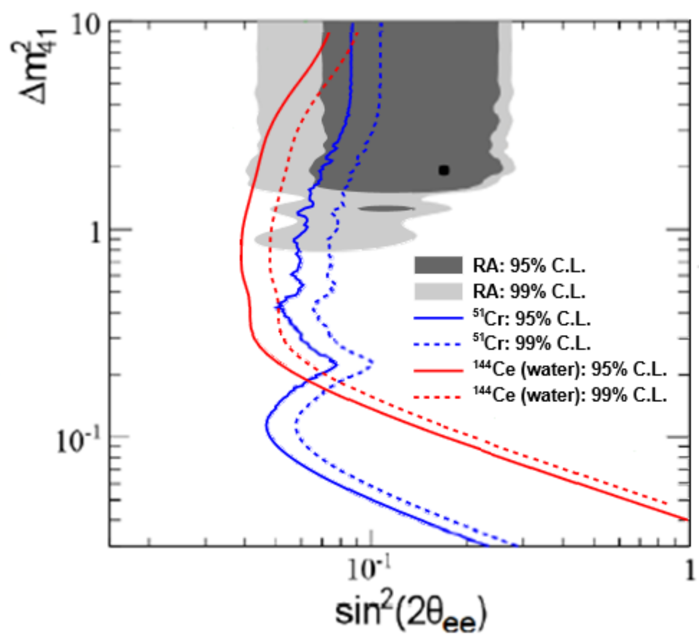
At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

^{144}Ce ν↓e neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.



^{144}Ce-^{144}Pr Decay





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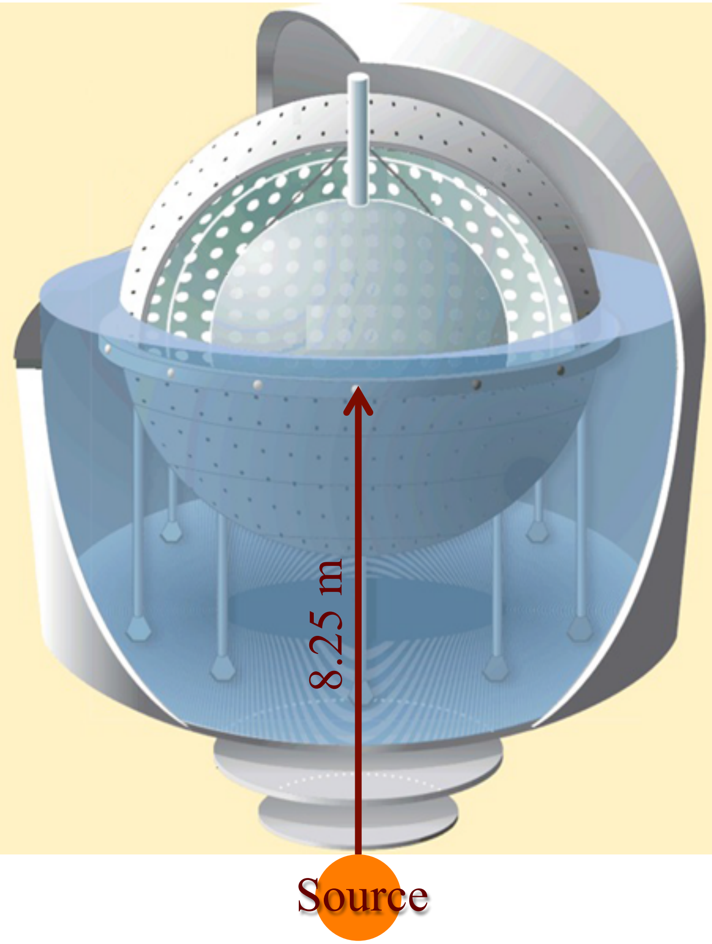

At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.

^{144}Ce ν↓e neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.

Mono-energetic ^{51}Cr ν↓e oscillate as a pure function of L, and are c scattering.

^{51}Cr Decay